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PRINCIPAL INVESTIGATOR: James H. Stuhmiller, Ph.D.

CONTRACTING ORGANIZATION: JAYCOR
San Diego, CA 92121

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James H. Stuhmiller, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
JAYCOR
San Diego, CA 92121

E-Mail: jstuhmiller@jaycor.com

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Contents

1. Introduction

1.1 Background

In the course of training, the soldier is exposed to a variety of blast sources (small and large caliber), in a variety of surroundings (in the open and inside enclosures), and for single and multiple rounds. The Surgeon General of the Army must set conditions that limit the exposure of troops to blast overpressure (or "weapon noise") that will result in only a very small incidence of deleterious effects in the soldier population.

Military Standard 1474C (1991) provides rules for determining exposure limits based on auditory hazard. The data used to formulate these limits came from small caliber (high frequency) fire. The Standard assumes that the blast field can be characterized by two parameters: the peak pressure and a time duration. Based on those two quantities, a maximum number of exposures are determined. If the combination of quantities exceeds the "Z-line," the Standard allows no exposures because of unspecified nonauditory danger.

When an exposure exceeds the Standard's nonauditory limits, man-rating studies must be conducted to establish exposure limits on a weapon-by-weapon basis. This is a time-consuming and expensive procedure that is likely to become more and more common as weapon power increases. Furthermore, when the blast overpressure hazard arises in an enclosure, the variation and permutations of the exposure become so enormous that case-by-case studies are not feasible.

When blast overpressure levels increase further, the concern switches from identifying threshold to anticipating soldier performance and effectiveness. Here, the guidance for Army doctrine has come from animal tests, largely concerned with lethality estimates. More recent animal tests and more thorough analysis of previous test data reveals that physiological effects are present at much lower values than had been previously thought and involve all of the body's air-containing organs.

Finally, animal studies that consider the effects of combined trauma have shown that the pathophysiological consequences can be profound, and could have implications both for the individual and for the medical care system. Once again, the elements entering such estimates do not properly reflect what is known about the physiological consequences of blast overpressure, nor is enough known to be able to confidently anticipate the consequences.

1.2 Previous Work

Animal Tests. Over the past 15 years, tests have been conducted at the Albuquerque Overpressure Test Site, under the sponsorship of the US Army Medical Research & Materiel Command (MRMC), exposing animals to blast loading. See Richmond, et al (1982), Dodd, et al., (1985), Yelverton, et al., (1993a), and Yelverton, et al., (1993b). Configurations included explosives detonated in the open and in enclosures and simulations of weapons fired from enclosures. The tests were conducted as studies with specific, narrow goals and the results were not systematically organized and analyzed in total.

Much of the experimental design was based on the assumption that respiratory injury had the lowest threshold and that injury to the upper respiratory tract preceded injury to the lung. An analysis of threshold injury levels, however, based on a preliminary compilation of the animal data showed an unexpected prevalence of injury to the gastro-intestinal tract (GI) and no significant difference in threshold between any of the air-containing organs. See Stuhmiller (1990).

Injury Mechanisms. Since the lung had been identified initially as the most critical major organ injured by blast overpressure, work was conducted to understand the mechanical properties of lung materials, so that models could be constructed. See Fung, et al., (1985). In addition, a theory was advanced connecting tissue damage to the compression wave within the lung. Fung, et al., (1988).

Using the knowledge of the biological material properties, a mechanical model of the thorax wall and lung parenchyma was developed (Yu, 1990). These studies elucidated the reasons why pressure measurements differ between the large airways and the parenchyma. Furthermore, a linear relation was observed between the velocity of the chest wall and the strength of the internal compression wave. This pivotal finding was also confirmed with mathematical simulations (Vander Vorst and Stuhmiller, 1990).

As concern over GI tract injury grew, exploratory work was undertaken to identify the underlying mechanisms. Surrogate models revealed that damage to the tract arises from concentrations of stress at locations near air bubbles (Vasel, et al., 1990). Once the mechanism was understood, the mechanical properties controlling this phenomena could be identified and experiments conducted to determine the values of these properties in small animal intestines (Yu and Vasel, 1990). A surgical procedure was developed for an isolated, perfused model of the rabbit gut in which systematic studies could be conducted (Yu, et al., 1991).

Mathematical Modeling. The first biomechanical models to predict response to blast overpressure were developed by White, et al., (1971). The model was calibrated to predict the esophageal pressure observed in large animal tests, but attempts to correlate this quan-

tity with lethality were unsuccessful. Later, Josephson et al., revisited the model and concluded that the predicted pressures could not be correlated with injury. Stuhmiller (1986) showed that the empirical correlation of injury with hyperbolic curves on a peak pressure-duration axes are related to the amount of irreversible energy loss in mass-spring-damper systems. These "generic" models formed a theoretical basis from which current biomechanical models, such as Viano and Lau (1988) have been developed.

The first systematic application of this biomechanical approach was made for the tympanic membrane (Stuhmiller, 1989). Finite element modeling was used to transform the geometric details of the membrane and support structures into a mass-spring-damper system. Rupture of the membrane was associated with exceeding the tensile strength of the membrane fibers. The resulting model provided an excellent correlation of observed tympanic membrane rupture in isolated specimens. A summary of the biomechanical modeling approach and its potential for blast overpressure related problems is found in Stuhmiller, et al., (1990).

Hazard Assessment. As mentioned earlier, the military standard for occupational exposure is primarily one for auditory effects. A nonauditory limit was proposed that is a parallel curve with peak pressures increased by about a factor of 2. For combat casualty purposes, a lethality criteria was developed by Bowen empirically based on animal data. A "threshold" injury curve was proposed that is a parallel curve with peak pressures reduced by a constant factor. Subsequent data analysis has shown that injury occurs at peak pressures less than these "threshold" estimates.

To provide a better criterion, Dodd, et al., (1990) proposed a peak pressure-duration curve to define conditions that would not produce "unacceptable" injury (any injury to the lung or GI tract or more serious injury to the upper respiratory tract (URT)). Separate curves were developed for multiple exposures. These relations have been used by MRMC as an interim criterion for making health hazards assessment of free-field weapon exposures.

All of the relations based on peak pressure and duration become unreliable in enclosures because reverberations make the duration so long that extreme injuries are always predicted. Attempts to find "equivalent" free-field waveforms are scientifically unjustified and have produced equally unreliable results. Consequently, MRMC began to experiment with using Jaycor's "generic" models to assess complex wave exposures.

In addition, the complex nature of blast waves in enclosures produces pressure traces that differ significantly from one location to another (because of the additions and cancellations caused by the myriad of wall reflections). The traces at a particular location also differ significantly depending on whether an animal is present or not (because of the shielding

and amplifying effects of the body). These variations are further confounded by the shot-to-shot variations seen in repeated tests.

1.3 Objectives of FY03 Work

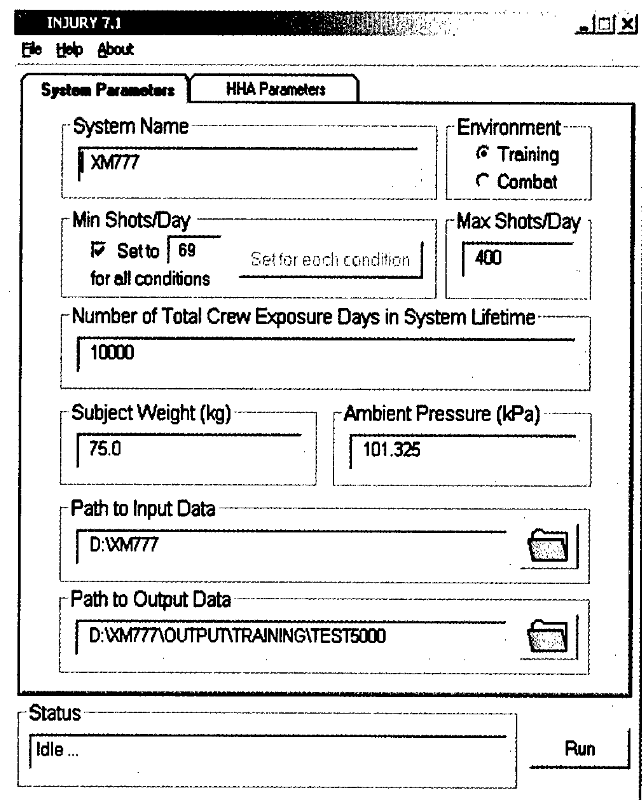
The biomechanical foundations established in previous years have been used to address new problems in blast overpressure, mechanical impact, head injury, rib fracture, and new thermobaric weapons.

2. Blast Overpressure

2.1 INJURY Computer Code

2.1.1 Background

The INJURY computer code is a product developed by Jaycor during FY02 under the sponsorship of MRMC, to fill the need for a standardized tool for performing nonauditory health hazard assessments (HHA). The injury model in the code addresses the contusive lung injury arising from repeated exposure to air blast, and includes a computational model for predicting the response of the chest wall, and the accompanying irreversible normalized work done on the lung. INJURY 7.1 has been extensively used by CHPPM and is an essential tool for carrying out their mission to perform nonauditory HHA for existing and emerging weapon systems. The correlation in INJURY 7.1 relating lung injury to irreversible work done on the lung is an ordered logistic regression derived from a study including 825 animals exposed to air blast in the free field and in enclosures. INJURY 7.1 differs from earlier code versions in three major respects. Prior versions did not employ the ordered logistic regression model, which was implemented and qualified during FY02. This model provides an improved level of consistency with observed animal injury data among all levels of injury. The second major enhancement in INJURY 7.1 is the capability of allowing a large set of BOP trace data to be specified with a minimum of user effort. This is achieved by adopting a test data directory structure and a file naming convention which follow a universal pattern. In light of the possibility of dealing with literally thousands of BOP traces, the original method of manually specifying each BOP trace proved highly impractical. A standardized format for the directory structure of



BOP test data allows simultaneous processing of all test data for a given study in a single step.

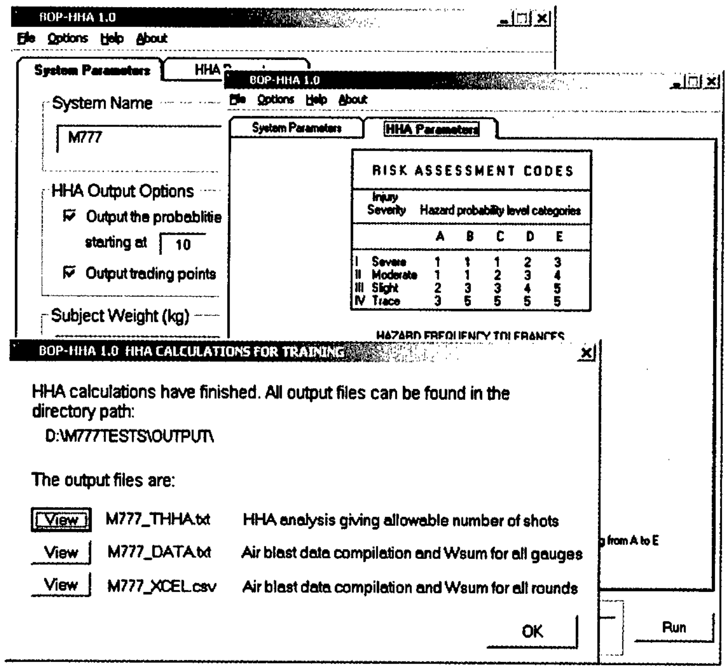
A third major improvement in INJURY 7.1 is the calculation of Risk Assessment Codes (RAC). In the early stages of transition of Jaycor's INJURY software to CHPPM, it became apparent that an important and ultimate requirement of a complete analysis tool for nonauditory HHA is the determination of a Risk Assessment Code. The RAC output data from INJURY 7.1 are consistent with Army Regulation 40-10 (1991) and ML-STD-882 (1993), and enable a health hazard assessor to make a rapid intelligent decision concerning the occupational safety of a given weapon system. Values of RAC depend on both hazard severity and hazard frequency. Hazard severity is accounted for by evaluating the likelihood of injury for each of four injury levels: trace, slight, moderate and severe injury. Probabilities of injury are calculated using an ordered logistic regression derived from observed injuries (percentages of contused lung surface area) of animal subjects exposed to air blast. The animal tests were performed at the Albuquerque Overpressure Test Site, over a period of nearly two decades. Under sponsorship of MRMC, the animal test data have been assembled, organized, placed into a central database, and analyzed by Jaycor.

INJURY 7.1 was released in December 2001, and has received wide use at CHPPM since that time. During FY03, significant improvements were made to the code, culminating in the release of INJURY 7.2, INJURY 7.3, and the most recent version of INJURY, denoted as BOP-HHA 1.0. These improvements are described in Section 2.1.2.

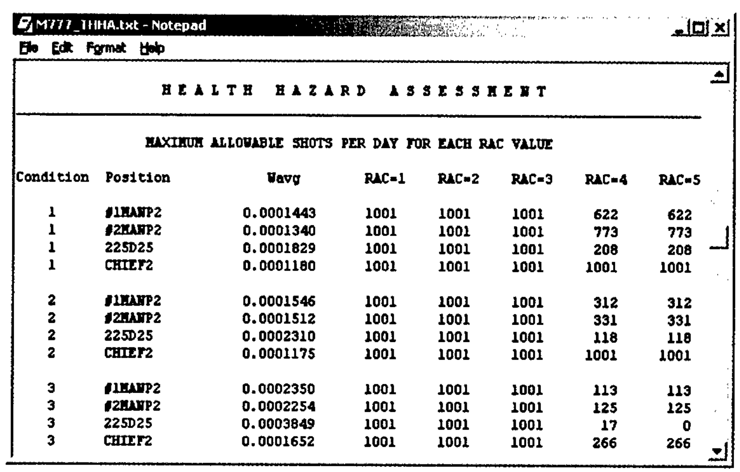
Product 1. INJURY 7.1 Computer Code for Nonauditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.

2.1.2 *INJURY Improvements: BOP-HHA 1.0*

During FY03, several major improvements were made to the INJURY 7.1 code released in the prior fiscal year. User feedback from CHPPM, as well as on-site use of INJURY 7.1 by the code developer at the Yuma Proving Grounds (YPG) illustrated the need for additional features and code enhancements. The need for an injury model that could address combinations of different exposures (e.g., charge weights, crew positions) was reiterated in a meeting at CHPPM in early 2003. Simplification of user input was also a primary goal, since key input parameters (e.g., number of shots per day and in system lifetime) were sometimes difficult to determine, often leading to delays in the ability to perform HHA for a given weapon system. Enhancements to the numerical scheme and to the physical model used to predict lung response were also important goals in this work. Specifically, the improvements made relative to INJURY 7.1 include:



- A simplified user interface, eliminating the need to input the desired number of shots per day and total number of exposures in the system lifetime.
- An improved and more efficient method of calculating the maximum allowable shots for each value of RAC. The new method is based on a first guess which is usually quite close to the final answer, resulting in a noticeable reduction in computation time.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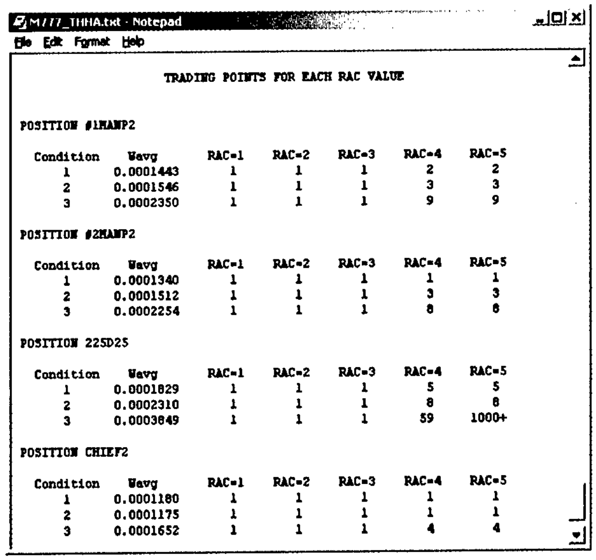
HEALTH HAZARD ASSESSMENT

MAXIMUM ALLOWABLE SHOTS PER DAY FOR EACH RAC VALUE

Condition	Position	Wavg	RAC=1	RAC=2	RAC=3	RAC=4	RAC=5
1	#1MANP2	0.0001443	1001	1001	1001	622	622
1	#2MANP2	0.0001340	1001	1001	1001	773	773
1	225D25	0.0001829	1001	1001	1001	208	208
1	CHIEF2	0.0001180	1001	1001	1001	1001	1001
2	#1MANP2	0.0001546	1001	1001	1001	312	312
2	#2MANP2	0.0001512	1001	1001	1001	331	331
2	225D25	0.0002310	1001	1001	1001	118	118
2	CHIEF2	0.0001175	1001	1001	1001	1001	1001
3	#1MANP2	0.0002350	1001	1001	1001	113	113
3	#2MANP2	0.0002254	1001	1001	1001	125	125
3	225D25	0.0003849	1001	1001	1001	17	0
3	CHIEF2	0.0001652	1001	1001	1001	266	266

- Improved, simplified, and expanded output in tabular form, providing the maximum allowable number of shots per day for each of five possible values of RAC. This output format eliminates the need for user input of the desired shots per day.

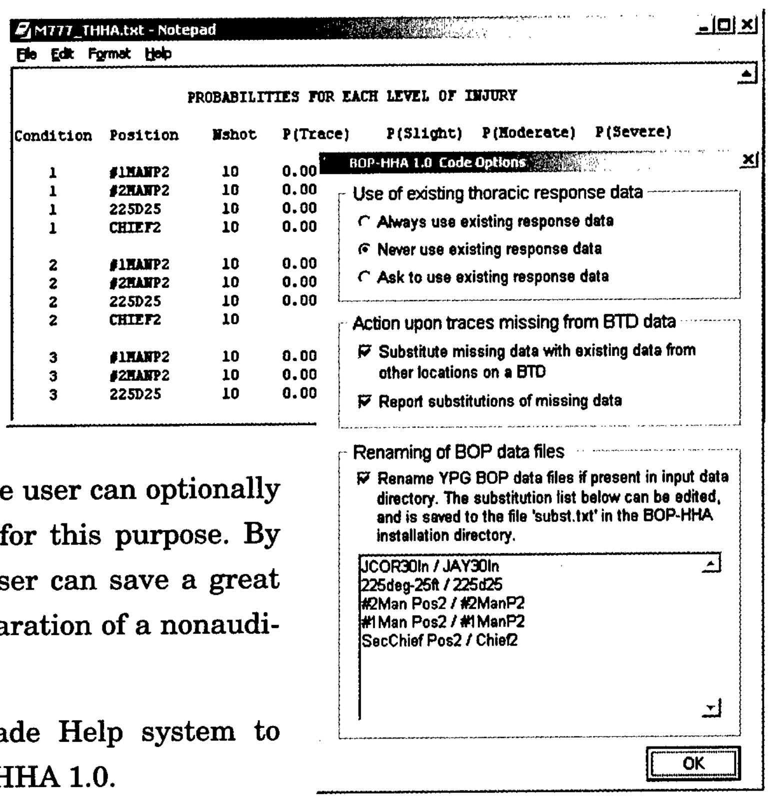


- Calculation and display of "trading points" which allow assessment of the likelihood of injury due to combined effects of exposure to different charges (e.g., charge types or zones) in a single day. Also allows assessment of a single crew member moving to different positions, and possibly exposed to different charges at each position.

- Option to output probabilities of injury for each injury level. If this option is selected, the user can specify the starting value, ending value, and increment for the number of shots per day used in the calculation of probability of injury.

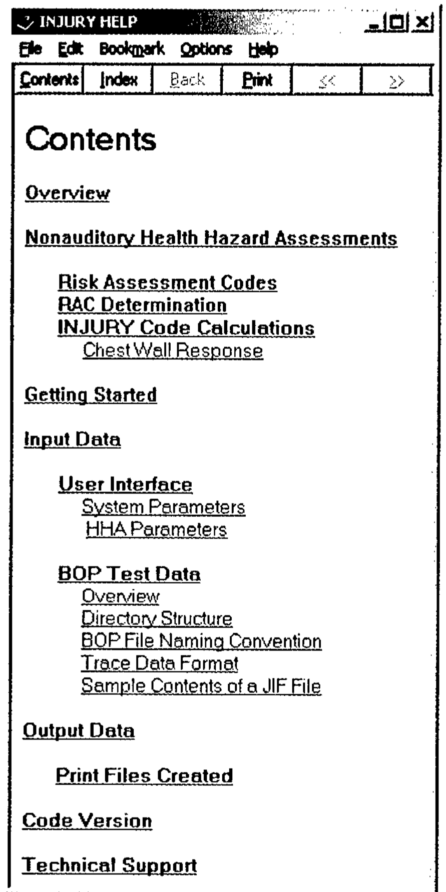
- Improved error reporting (e.g. in the event of missing data, a file path error, or an error in the lung response calculation).

- Option to automatically rename BOP trace files that appear to follow the Yuma Proving Ground (YPG) file naming convention. In a new user dialog, the user can optionally specify replacement strings for this purpose. By exercising this option, the user can save a great deal of manual labor in preparation of a nonauditory HHA.



- An updated commercial grade Help system to reflect new features in BOP-HHA 1.0.

- An improved numerical method used in lung response calculations. The solution to the system of masses, springs and dampers used to model the chest wall and lung cavity is now obtained by a fifth order Runge-Kutta technique, resulting in improved accuracy. In addition, this method allows a larger time step resulting in computation times that are approximately 1/3 of the times required by previous versions of INJURY.



- As a result of identifying possible numerical artifacts due to the skin component of the lung response model, the mass element (m1) representing the skin has been removed from the model. This results in a more accurate description for the velocity of the chest wall used to calculate normalized irreversible work done on the lung. The skin component is deemed to be appropriate for the type of impulse associated with automobile crash environments, but in extensive quality assurance testing it was shown to be inappropriate for BOP loading.

- A new ordered logistic regression for probability of injury has been formulated, based on applying the lung response model without the skin component to the animal data. The new regression was found to not differ dramatically from that used in INJURY 7.1, but for overall consistency, it has been incorporated in BOP-HHA 1.0.

- The lung response model has been assembled into a distinct module that can now be used by other applications. This module accepts front and rear pressure loading as inputs, and includes prediction of the time dependent behavior of the chest wall and subsequent calculation of the normalized work done on the lung.

Product 2. BOP-HHA 1.0 Computer Code for Nonauditory Health Hazard Assessment, Jaycor, Release date October 6, 2003.

Product 3. Masiello, P. J., and J. H. Stuhmiller (2003). "A Thoracic Injury Criterion for Exposure to Air Blast," Final Report J299753-03-105, October 2003.

2.2 Blast Test Device Comparisons

2.2.1 Introduction

During the last two decades, an extensive animal testing program was sponsored by the Walter Reed Army Institute of Research (WRAIR) for the purpose of quantifying the potentially injurious effects of blast overpressure (BOP) exposure. A primary goal was to establish suitable criteria for occupational health hazard assessment (HHA) of nonauditory injury that soldiers might be subjected to in training and in combat. Jaycor played a major role in that program, developing a blast test device (BTD) for measurement of pressure loading on the thorax, assimilating and organizing BOP data, and developing an injury correlate and associated methodology for nonauditory HHA. The U.S. Army Center for Health Promotion and Preventative Medicine (USACHPPM) presently employs the INJURY computer code developed by Jaycor as an important tool for making nonauditory health hazard assessments for a given weapon system.

Early difficulty in measuring reliable blast overpressure using gauges attached to the epidermis of animal subjects led to the need for a mechanical device for pressure measurement. Subsequent to its design and construction, the Jaycor BTD was used extensively in the animal test program for the collection of BOP data. Typically, a BTD would be placed in the same position that an animal subject would occupy in a repeated trial of the same experiment. In that manner, reliable data for BOP could be collected, and injury data could be obtained by means of pathology of an animal exposed to the same blast conditions.

2.2.1.1 BTD Designs

The Jaycor BTD was designed to occupy approximately the same cross-sectional area as a sheep or human thorax at mid-chest level. The BTD is an aluminum cylinder 30" in length, with an outer diameter of 12". Four 1000 psi PCB Electronics 102A04 piezoelectric pressure transducers are evenly spaced along the circumference at mid-height (15" from either end) of the cylinder, for measurement of local pressure at analogous locations of the sternum, right side, spine, and left side of the thorax. The relatively high limit of maximum pressure allows use of the BTD over a wide range of test conditions, as encountered in the full set of animal experiments conducted at the Albuquerque Overpressure Test Site.

In recent years, weapons testing centers such as the Aberdeen Proving Ground (APG) and Yuma Proving Ground (YPG) have used smaller and lightweight BTD designs in place of the Jaycor BTD, apparently motivated by ease of placement in confined areas. One such design is the 24" BTD, also of a cylindrical shell design, but with pressure gauges located 6" from the top edge of the BTD. The salient differences with the Jaycor blast test device are summarized below:

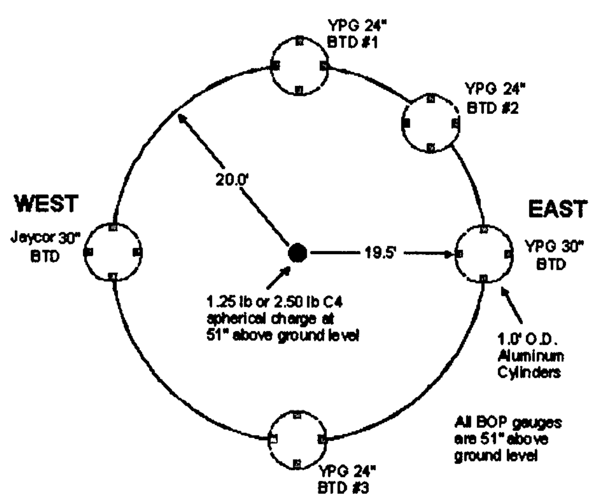
- The cylinder height of a typical YPG blast test device is 24" as opposed to 30".
- Pressure gauges of the YPG design are mounted 6" from the top edge of the cylinder, as opposed to a mid-height elevation of 15" for the Jaycor unit.
- The YPG design utilizes Endevco Model 8530C Piezoresistive pressure transducers having a maximum range of 15 psi (some designs use a range of 30 or 50 psi).
- The YPG BTD utilizes a cylindrical shell of 0.25" wall thickness, as opposed to the 0.75" thick wall of the Jaycor BTD.
- The YPG units lack the two 0.75 inch thick internal stiffener disks that the Jaycor design employs.

2.2.1.2 Objective

The objective of this study is to determine the effect that a smaller BTD design has on the normalized work done on the lung, an important correlate of nonauditory injury that can be deduced from the measured BOP data. In this study, the Jaycor INJURY 7.2 computer code is used to calculate the normalized work *W* from the overpressure measured by the Jaycor and YPG blast test devices. Normalized work, derived from a response model of the lung given the measured BOP loading, is used as a correlate for contusive lung injury, and is a key parameter in making nonauditory health hazard assessments (HHA).

2.2.2 Test Configuration

The BTD testing was performed at YPG on April 22-23, 2003. The blast test devices were arranged in a circle with radius of 20 feet on approximately level desert terrain. The initial tests were carried out with a 1.25 lb spherical C4 charge placed at the center of the circle at average chest height, 51 inches above ground level. A total of five BTDs were placed at various locations along the circumference of the circle. The ensemble of BTDs consisted of: (1) one Jaycor 30" BTD, (2) one YPG 30" BTD, and three YPG 24" BTDs. The Jaycor BTD was placed at the 0° reference position (approximately due West), and the YPG 30" BTD at 180°, with the 24" units located at 90°, 135°, and 270°. The 30" YPG BTD was specially assembled for comparison with the Jaycor 30" BTD, and is not typically used



Nominal configuration of BTD comparison tests.

for YPG weapons testing. The YPG 30" unit is of the same basic design as the 24" BTD, with the exception of the length of the cylindrical shell, and the location of the pressure gauges relative to the top of the BTD. Nominally, the pressure transducers were mounted at mid-height (15" from the top) of the 30" YPG cylindrical shell, but special provision was made for ease of placement of the gauges to the 6" position reflecting the design of the YPG 24" BTDs. Endevco Model 8530C pressure transducers were employed in both the YPG 24" and 30" units.

2.2.2.1 Test Matrix

The test matrix for the BTD comparisons, which includes 10 distinct test conditions, is shown in Table 1. Separate effects that were tested include the effect of AC coupling (high pass filtering) in the signal processing path for the Jaycor BTD, the low pass (LP) filter frequency for all BTDs, the location of pressure transducers along the length of the YPG 30" BTD, and the physical (East/West) location of Jaycor and YPG 30" BTDs. As Table 1 indicates, Conditions 1 to 7 apply to the 1.25 lb C4 charge located 20 feet from the BTD centerlines. Conditions 8 and 9 explore the effects of a smaller distance to charge of 15 feet, and Condition 10 focuses on the effect of a larger charge weight of 2.50 lb at the range of 15 feet. In order to test for a separate effect, only a single parameter was varied from condition-to-condition. A sufficient number of charges were detonated so that data for at least three usable rounds were obtained for each condition. Due to occasional instrumentation malfunctions, more than three charges had to be detonated for several conditions. A total of 36 C4 charges were expended during the testing period. The positions of the Jaycor 30" BTD and YPG 30" BTD were interchanged starting at Condition 3, and the new positions retained through the end of the testing. This procedure provided a simple test of the possible effects of uneven terrain, BTD placement, and wind speed.

Table 1. Test Matrix for BTD Comparison Study.

Condition	Date	Rounds	Description	Comments
1	4/22/2003	1-3	1.25 lb C4 @ 20ft, LP filter @ 35.667 kHz all channels. AC coupling on JAYCOR BTD gauges.	Round 1 has Jaycor gauges reversed
2	4/22/2003	4-6	1.25 lb C4 @ 20ft, LP filter @ 35.667 kHz all channels. No AC coupling on JAYCOR BTD gauges.	
3	4/22/2003	7-11	1.25 lb C4 @ 20ft, LP filter @ 35.667 kHz all channels. No AC coupling on JAYCOR BTD gauges. JAY30In and YPG30In positions are switched.	Rounds 9-11 give much higher W than 7-8 and previous shots in Conditions 1 & 2
4	4/23/2003	12-17	Repeat of Condition 3 from previous day.	Round 12 bad (filter problem) Rounds 14-15 BTD #1right gauge bad Rounds 16-17 OK
5	4/23/2003	18-20	Repeat of Condition 1 from previous day, but with JAY30In and YPG30In positions switched, as in Condition 3.	
6	4/23/2003	21-24	Electronics configured as in March 24, 2003, including AC coupling on JAYCOR BTD gauges. JAY30In and YPG30In positions switched, as in Condition 3.	Round 22 #2 BTD chest gauge bad 22 Round 23 #2 BTD left gauge bad
7	4/23/2003	25-27	Like condition 6, only YPG 30" gauges moved to 6" from top.	Round 26 BTD #1 left bad
8	4/23/2003	28-30	1.25 lb C4 @ 15ft. LP filter @ 35.667 kHz all channels. No AC coupling on JAYCOR BTD gauges. YPG 30" gauges are 6" from top as in Condition 7.	
9	4/23/2003	31-33	1.25 lb C4 @ 15ft. LP filter @ 35.667 kHz all channels. No AC coupling on JAYCOR BTD gauges. YPG 30" gauges moved to mid-height as in Conditions 1-6.	
10	4/23/2003	34-36	2.5 lb C4 @ 15ft. LP filter @ 35.667 kHz all channels. No AC coupling on JAYCOR BTD gauges. YPG 30" gauges are mid-height as in Conditions 1-6.	

2.2.3 Method

Comparisons of results for the five blast test devices consider the effect that a given design has on the value of normalized work done on the lung. Normalized work is calculated by the lung response model of the INJURY 7.2 computer code. The response model requires a set of four overpressures measured by means of a blast test device, representing the pressure loading on four circumferential locations along the periphery of a human thorax.

The comparisons of normalized work for the different BTDs are accomplished by means of statistical and graphical methods. The method of linear regression is employed in conjunction with visualization of trends in the data using scatter plots and "box and whisker" graphs, which compare the mean values of two distributions and their relationships to the standard error and standard deviation. Linear regressions are used to relate the normalized work from one BTD to that of another. If the work derived from two BTDs is identical, the resulting regression will be a straight line with a slope of 1.0 and an intercept of 0.0. Differences in work are evident by slopes that are less than or greater than 1.0. The randomness or uncertainty in the data is evident by the observed deviation of each data sample from the linear fit.

The method of linear regression determines the best fit by minimizing squared differences of the data with the prediction. Since it is expected that all BTDs should give zero normalized work for zero overpressure, the option of a linear fit with zero intercept was employed in the regression analyses. Confidence bands of the linear regression at 95% probability were also determined. Linear regressions were determined using the Analysis Toolpak of MS Excel 2000 and also the STATISTICA 6.0 computer code.

2.2.4 Results

A summary of normalized work W averaged over three rounds for each condition and for each blast test device is presented in Table 2. The last column of the table is the average of the mean values of W over the three YPG 24" BTDs, and can be compared with the second and third columns, which apply to the Jaycor and YPG 30" BTDs, respectively. Special care must be taken in comparing results for separate effects, since observed differences might be due to condition-to-condition variability (e.g., repeatability of the experiment) and not to the effect of some test parameter. The condition-to-condition and round-to-round variability might be associated with properties (e.g., lack of homogeneity) of the particular C4 charge or series of charges in use at the time of testing, even though the charge weight is the same. In the bottom rows of Table 2, averages of mean values for W are shown for various combinations of conditions (e.g., "AVG 1-7" denotes a combination of data for Conditions 1 through 7, which apply to a charge weight of 1.25 lb at 20'). In the last

row of Table 2 are data for the standard deviation of the seven mean values for Conditions 1-7, divided by the ensemble mean for the same conditions. These data show that condition-to-condition percentage differences as low as 5.3% for YPG 24" BTD #3, and as high as 13.8% for the Jaycor 30" BTD. While no test conditions have changed (other than low pass filter frequency, later shown to be insignificant) for the YPG 24" units, effects such as AC coupling have changed for the Jaycor BTD over this set of conditions. Hence, it is reasonable to expect that the percentage differences will be higher for the Jaycor device. Condition-to-condition differences for the YPG 30" BTD are of the order of 8% for the same data, but are also subject to changes in some separate effects being tested.

Table 2. Average normalized work for each condition for Jaycor and YPG blast test devices. The standard deviation of normalized work over Conditions 1 through 7 is also included.

Condition	**Average normalized work W over 3 rounds per condition**					
	JAY 30"	**YPG 30"**	**YPG 24" #1**	**YPG 24" #2**	**YPG 24" #3**	**AVG YPG 24" #1- #3**
1	0.0001979	0.0002168	0.0002337	0.0002291	0.0002421	0.0002350
2	0.0002125	0.0002063	0.0002300	0.0002210	0.0002369	0.0002293
3	0.0002748	0.0002466	0.0002638	0.0002691	0.0002720	0.0002683
4	0.0002331	0.0002108	0.0002237	0.0002253	0.0002357	0.0002282
5	0.0002010	0.0002512	0.0002519	0.0002453	0.0002569	0.0002514
6	0.0002056	0.0002581	0.0002486	0.0002478	0.0002571	0.0002512
7	0.0001858	0.0002416	0.0002361	0.0002284	0.0002441	0.0002362
8	0.0003319	0.0003595	0.0003643	0.0003510	0.0003684	0.0003612
9	0.0003511	0.0003845	0.0003894	0.0003768	0.0003833	0.0003832
10	0.0008667	0.0008904	0.0009225	0.0008978	0.0009056	0.0009086
AVG 1-7	0.0002158	0.0002331	0.0002411	0.0002380	0.0002493	0.0002428
AVG 2-4	0.0002401	0.0002212	0.0002392	0.0002385	0.0002482	0.0002419
AVG 1, 5-7	0.0001976	0.0002419	0.0002426	0.0002377	0.0002501	0.0002434
AVG 8-9	0.0003415	0.0003720	0.0003769	0.0003639	0.0003759	0.0003722
DEV 1-7	0.0000298	0.0000212	0.0000141	0.0000170	0.0000132	0.0000147
DEV/AVG 1-7	0.1381650	0.0908243	0.0585042	0.0715150	0.0531100	0.0604633

Notes:

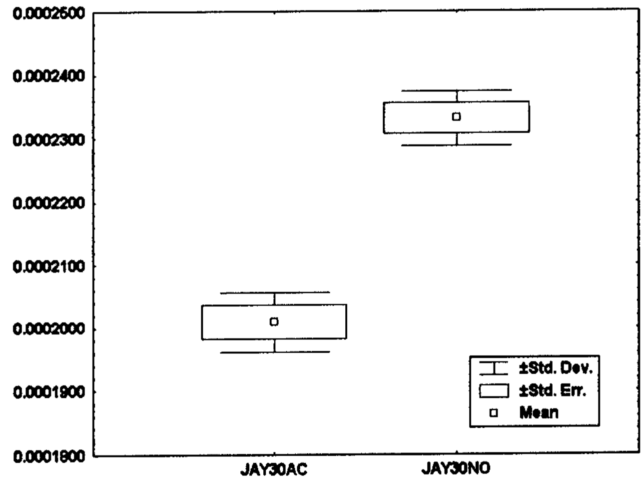
(1) "AVG m-n" in the condition column denotes the mean value over Conditions m through n.

(2) "DEV m-n" in the condition column denotes the standard deviation over Conditions m through n.

(3) "DEV/AVG m-n" in the condition column denotes the standard deviation divided by the mean value for Conditions m through n.

2.2.4.1 *Effect of AC Coupling on W for the Jaycor BTD*

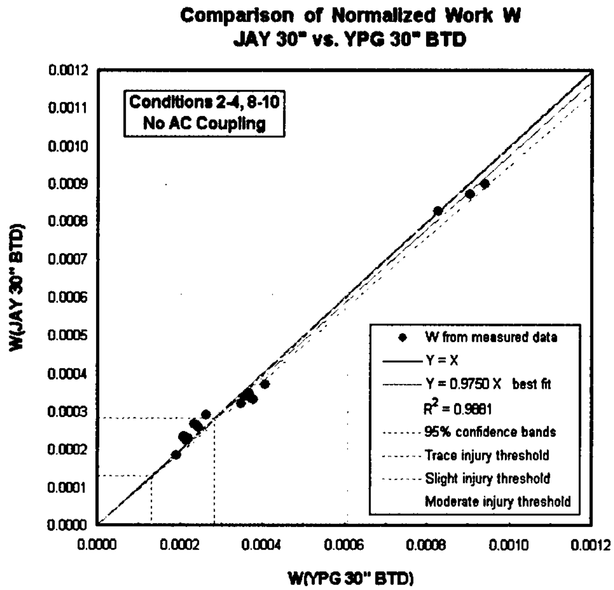
AC coupling of the BOP traces obtained from the Jaycor BTD was found to have the most significant effect among all changes in test conditions. A simple comparison of *W* for Conditions 1 and 2 shows a noticeable increase of about 7% for the Jaycor 30" BTD when AC coupling is removed. AC coupling is essentially a high pass filter that affects the decay time of the pressure peak, resulting in a decrease in the impulse of the pressure time history, and an accompanying decrease in normalized work.



Effect of AC coupling on *W* for Jaycor 30" BTD. JAY30NO: no AC coupling, JAY30AC: AC coupling.

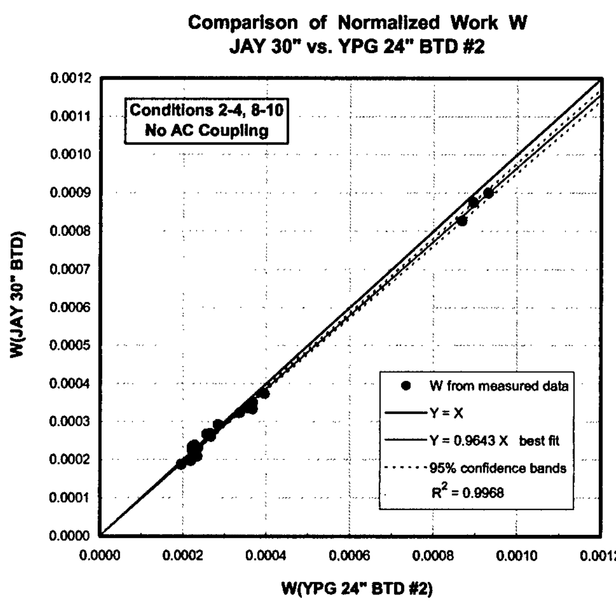
This effect can also be seen easily by comparing *W* for Conditions 4 and 5. For this comparison, we ignore the difference in East/West position of the Jaycor BTD, shown to be insignificant in this study. We observe that for the Jaycor BTD, *W* with AC coupling removed is about 16% greater than it is when AC coupling is present. A box and whisker plot comparing the mean values and standard errors of *W* for Conditions 4 and 5 is shown in the figure. AC coupling clearly has a significant effect. The standard error intervals (rectangles in the above figure) around the mean values are displaced quite far apart and do not overlap.

A scatter plot comparing *W* for the YPG 30" BTD and Jaycor 30" BTD with no AC coupling is shown in the following figure, reflecting only data for those conditions for which the Jaycor BTD is not AC coupled (Conditions 2-4 and 8-10). Data at the high end of the range of normalized work, $W > 0.0008$, apply to Condition 10, with a charge weight of 2.5 lb at a range of 15 feet. The normalized work for each usable round of each condition is plotted in the figure, comprising a total of 22 data samples. The result of a linear regression with zero intercept is shown in the figure as the red solid line. The best fit to the data is given by Y=0.9750 X, where X and Y denote *W* for the YPG and Jaycor 30" BTDs, respectively. The slope of 0.9750 is close to 1.0, and implies an average difference in *W* of only 2.5%. The figure also includes 95% confidence bands (the dashed red lines) for the linear regression, which occupy a very narrow region around the linear fit. This is consistent with the high value of the "coefficient of determination", $R^2 = 0.9881$, indicating a fit that is deemed as excellent.



Scatter plot and linear regression comparing *W* for the Jaycor 30" BTD and YPG 30" BTDs.

A scatter plot comparing normalized work for the Jaycor 30" BTD with that for YPG 24" BTD #2 is shown in the next figure. The data included in the figure apply only to those conditions for which the Jaycor BTD is not AC coupled. The slopes of linear regressions relating W for the Jaycor BTD with that of YPG 24" BTDs #1, #2, and #3 are all relatively close to 1.0, varying from 0.9392 to 0.9643. The linear fits with slopes less than 1.0 imply a consistent overprediction for the 24" BTDs relative to the Jaycor 30" device, with average differences in *W* ranging from 4% to 6%.



Scatter plot and linear regression comparing *W* for the Jaycor 30" BTD and YPG 24" BTD #2.

A summary of average percentage differences in *W* for all BTD comparisons is presented in Table 3. In this table, differences are determined from the data for *W* averaged over each round of usable data for each condition. In the comparisons which indicate no AC

coupling for the Jaycor BTD, percentage differences are based only on data for Conditions 2-4 and 8-10. Otherwise, data from all 10 conditions have been employed in the calculation of average percentage differences. In the case of no AC coupling, normalized work from the Jaycor BTD compares quite well with that from the YPG 30" and 24" blast test devices, with average differences of -0.4% and +4.4%, respectively. With removal of AC coupling, the YPG 30" BTD slightly underpredicts *W* relative to the Jaycor BTD, while the YPG 24" BTD overpredicts normalized work by a small amount (e.g., about 4%). The YPG 30" BTD overpredicts work by 3.4% on average, relative to the YPG 24" BTDs. Differences in W among the three 24" BTDs are bounded by about 4%. Table 3 also indicates that the round-to-round variability is approximately 8%, and the condition-to-condition variability for the same test conditions is in the range of about 6 - 8%. Hence, the differences in *W* among the five blast test devices are typically smaller than those indicated by the observed condition-to-condition variability (e.g., repeatability of the experiment with the same test conditions).

Table 3. Summary of key percentage differences for BTD comparisons.

Comparison for Normalized Work *W*	% Difference
YPG 30" vs. Jaycor 30", all data	+8.8
YPG 30" vs. Jaycor 30", no AC coupling for Jaycor BTD	-0.4
YPG 24" vs. Jaycor 30", all data	+11.9
YPG 24" vs. Jaycor 30", no AC coupling for Jaycor BTD	+4.4
YPG 24" vs. YPG 30"	+3.4
YPG 24" #3 vs. YPG 24" #1	+2.2
YPG 24" #3 vs. YPG 24" #2	+4.1
YPG 24" #2 vs. YPG 24" #1	-1.9
Average round-to-round variation over all rounds	7.9
Average condition-to-condition variation, conditions 1-7	8.4
Average condition-to-condition variation, conditions 8-9	6.1
Range of condition-to-condition variation	0.1 – 17.0

Notes:

(1) Percentage difference of Y vs. X is defined as 100*(Y-X)/X.
(2) Comparisons with YPG 24" BTD denote comparisons with average *W* over all three 24" BTDs.
(3) Condition-to-condition variations are from comparisons of average *W* over all three 24" BTDs, relative to successive conditions.

2.2.4.2 Effect of Choice of BTD Design on Health Hazard Assessments

With or without AC coupling, the Jaycor BTDs typically give lower values of normalized work than YPG blast test devices, leading to a conservative estimate of injury, if the YPG BTDs are used in place of the Jaycor units in weapons testing. It is possible to provide an indication of the effect of a conservatively high measurement of normalized work on an injury estimate of the number of allowable shots per day, n, for a weapon system. The INJURY 7.2 computer code provides estimates of n based on BOP measurements carried out for a given weapon system, and is an essential tool in making a health hazard assessment (HHA) for nonauditory injury. Based on the logistic regression for the probability of injury employed by INJURY 7.2, the following relationship exists between normalized work W and n, for a given probability,

$$W * n^{(b_2/\, b_1)} = constant \tag{2-1}$$

where b_1 and b_2 are constants in the logistic regression: $b_1 = 1.877170$ and $b_2 = 0.7751848$. If we consider two point pairs of (W_1, n_1) and (W_2, n_2) leading to the same probability of injury, we have

$$W_1 n_1^{(b_2/\, b_1)} = W_2 n_2^{(b_2/\, b_1)} \tag{2-2}$$

Solving Eq. 2-2 for n_2, we have,

$$n_2 = n_1 (W_1 / W_2)^{(b_1/\, b_2)} \tag{2-3}$$

If the W resulting from a YPG 24" BTD is typically 4.4% larger than that obtained from a Jaycor 30" BTD (see Table 3), then $W_1 / W_2 = 1/1.044 = 0.9579$. Substituting values of b_1 and b_2 and $W_1 / W_2 = 0.9579$ in Eq. 2-3, we obtain a relationship between the number of allowable shots per day n_1 based on YPG 24" BTD measurements in terms of the number n_2 that would be obtained if the Jaycor 30" BTD was employed,

$$n_2 = 0.9010\, n_1 \tag{2-4}$$

Hence, the number of allowable shots would be reduced by 10% if the YPG 24" BTD was used in place of the Jaycor 30" blast test device.

2.2.5 Summary and Conclusions

Comparisons of normalized work, W, the parameter correlated with lung injury, were made with the INJURY 7.2 computer code, using overpressure data measured by blast test

devices (BTD) of three distinct designs: (1) Jaycor 30" BTD, (2) YPG 30" BTD, and (3) YPG 24" BTD. Blast overpressure measurements were performed to determine the effect of AC coupling (high pass filtering) in the signal path of the Jaycor BTD, low pass filter frequency, the height of the pressure transducers on the YPG 30" BTD, and the physical (East/West) location of the 30" BTD. The test matrix included 10 conditions, with at least three usable rounds of C4 per condition. The results of the comparisons show that:

- Changes in low pass filter frequency, BTD position, and YPG 30" gauge location were not found to be significant.
- AC coupling of the Jaycor 30" BTD resulted in a 16% increase in W.
- There are no significant differences between the YPG 30" BTD and the Jaycor 30", when there is no AC coupling.
- The YPG 24" BTDs produce W values 4% higher than the Jaycor 30", which corresponds to a 10% decrement in allowed number of shots per day, leading to a conservative estimate of the potential for lung injury.
- Shot-to-shot variations in the blast overpressure resulted in variations in W of 8% (standard deviation), which are greater than any of the variations among the various BTDs.

Results of this BTD comparison study can be applied only to weapon test configurations in open space, such as unprotected lightweight artillery. In confined configurations, such as Armored Personnel Carriers and bunkers, additional studies must be conducted to determine if wave reflections from nearby walls or other objects affect BOP measurements made with BTDs of various dimensions.

Product 4. Masiello, Paul J. (2003). "Blast Test Device Comparisons," Jaycor Technical Report J2997.24-03-196, June 2003.

3. Side Impact Rib Fracture Injury Analysis

3.1 Background

Human fatalities due to side impact account for approximately one-third of all traffic fatalities. The goal of minimizing side impact injuries will become increasingly important as the use of air bags reduces fatalities in vehicle collisions. A great deal of attention has being given recently to the effective design and implementation of side air bags. An automobile safety standard for side impact was established in October 1970, as Federal Motor Vehicle Safety Standard (FMVSS) 214, *Side Impact Strength – Passenger Cars*. This standard focused on increasing side door strength to minimize intrusion into the passenger compartment, and incorporated a quasi-static load test using a rigid cylinder placed against the side of a vehicle. In October 1990, a new rule was appended to the Code of Federal Regulations, imposing an additional dynamic requirement, FMVSS 214: *Side Impact Protection*. This new rule set forth specific requirements for a dynamic test procedure simulating a 90° impact on a moving vehicle, to include measurements of acceleration at various locations on specially designed Side Impact Dummies (SID), positioned in front and rear occupant positions on the side of the vehicle being impacted. The test data measured from SID instrumentation include the rib, spine and pelvic accelerations, which must not exceed certain threshold values for compliance with FMVSS 214.

The present U.S. safety standard for side impact does not include a reference to either lateral or frontal thoracic deflection, despite the fact that the latter does play a role in FMVSS 208, applicable to frontal impact. It is apparent from the biomechanics literature that there are conflicting findings with regard to what constitutes a suitable injury correlate for thoracic injury due to either frontal or side impact. The acceleration-based criteria referenced in FMVSS 208 and FMVSS 214 are deemed by many to not have a firm biomechanical basis. The overwhelming majority of injuries sustained by the thorax in automobile accidents are rib fractures. Variables that can be related in some way to the fracture stress of bone can be considered to be biomechanically based, such as chest deflection and curvature. These variables are the focus of the present study, which utilizes the same data employed by Kuppa, Eppinger, et al. (2000), but explores a wider range of biomechanically based risk factors. Of particular interest is the curvature (or more precisely, the change in curvature relative to the initial value) of horizontal cross-sections of the thorax, a quantity that can be measured directly by means of utilizing existing chest band instrumentation.

3.2 Test Data Description

Side impact sled tests using post-mortem human subjects were performed at the Medical College of Wisconsin (MCW) and also at NHTSA's Vehicle Research Test Center at Ohio State University (OSU). The sled apparatus at both test centers is of the Heidelberg design (Kallieris, 1981), configured for left side impacts against rigid and padded walls.

Both test centers utilized chest band instrumentation on test subjects, consisting of two 40-channel chest bands at levels of rib 4 and rib 7, for measurement of curvature at approximately every 2.5 cm around the chest perimeter. The local measurement of curvature allows the time dependent shape of a transverse cross-section of the thorax to be determined.

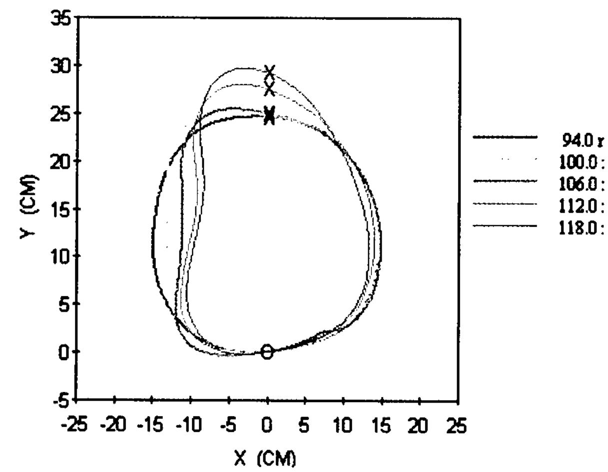
Injury severity was quantified in accordance with the AIS 90 standard (Abbreviated Injury Scale, 1990). Most of the trauma to the thorax consisted of multiple rib fractures with occasional hemopneumothorax (pleural tears caused by fractured ribs). According to AIS 90, AIS=1 is characterized by only one rib fracture, AIS=2 results from 2-3 fractures, and AIS=3 is assigned when there are more than 3 fractures on only one side of the ribcage. A score of AIS=4 is assigned when there are more than 3 fractures on each side. The presence of a hemopneumothorax or a flail chest increases the AIS score by 1.

Average age at death of subjects sustaining AIS ≥ 3 injury is 70.9 ± 9.2, while the average for those with AIS < 3 is only 56.5 ± 16.4. This implies that age is a confounder variable (an independent variable associated with both the dependent variable and other risk factors), a result also arrived at by Kuppa, Eppinger et al. (2000).

3.3 Methods

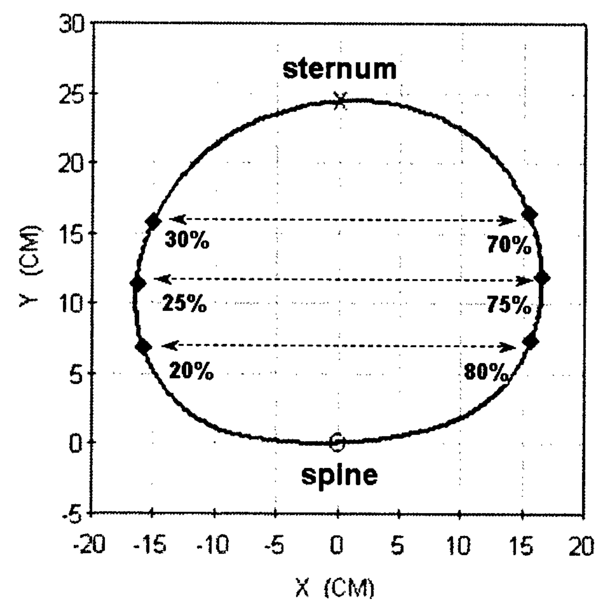
The selection of risk factors for thoracic injury is limited by the available measured data, or quantities that can be derived from them. Measured data consist of local curvature of the thoracic cross-section, impact load forces, and acceleration measured at the sternum, ribs, spine, sacrum and pelvis. Curvature data are used to calculate chest band contours, from which chest wall deflection can be determined. The RBANDPC software module included in NHTSA's SIMon (Simulated Injury Monitor) computer program was used to calculate chest band contours from the curvature data recorded for each band. Contours were calculated at 1 ms intervals over a total interval of 200 ms for each band.

Sample chest band contours for a typical left side impact are illustrated, where contours are shown at 6 ms intervals. The spine ("o") is located near the bottom center of the figure, and the sternum ("x") near the top. The origin of each contour (X=0, Y=0) is chosen arbitrarily as the point at which the band crosses the spine, where X is the lateral direction and Y is the anterior-to-posterior direction.



Chest band contours for lateral impact.

A lateral deflection deemed to be representative of side impact is defined as the maximum of the change in distance between three pairs of points located at specified fractional distances along the band length, proceeding in a clockwise direction and starting at the location of the spine. The three point pairs are defined at 20%-80%, 25%-75% and 30%-70% of the circumferential distance along the band. A value of *dmaxn* is calculated for each chest band contour, and is taken as the larger of the two values over all time for the upper and lower chest bands. Hence, *dmaxn* is the maximum of six distances, each representative of a local lateral deflection of the full thoracic cross-section.



Locations along chest band for lateral deflection computation.

The complete set of risk factors evaluated for use as potential thoracic injury correlates is given in Table 4. The Thoracic Trauma Index *TTI* (Eppinger, 1984) is determined from subject age, and lateral rib and spinal accelerations as

$$TTI = 1.4 * age + \frac{1}{2}(rib100 + spl100) * \frac{mass}{75kg} \tag{3-1}$$

where

$$rib100 = max(1.3*rlu100 - 2.02, rll100) \tag{3-2}$$

Table 4. Risk Factors Evaluated as Injury Correlates in Side Impact Analysis.

Symbol	Description
latdefln	Maximum normalized lateral single-point deflection
crdefln	Maximum normalized point-by-point deflection along chest band contours
avdefmxn	Spatial average of maximum normalized deflection at each point along a contour
dmaxn	Maximum normalized deflection between points at 2% and 80%, 25% and 75%, and 30% -70% along band, measured in a clockwise direction from spine
crvmaxn	Maximum normalized curvature along chest band contours
crvdiffn	Maximum normalized curvature difference along chest band contours
spnlrsn	Maximum normalized resultant lower spinal (T12) acceleration
spnursn	Maximum normalized resultant upper spinal (T2) acceleration
spl100	Maximum normalized lower spinal lateral acceleration (FIR100 filter)
spl180	Maximum normalized lower spinal lateral acceleration (SAE180 filter)
rll100	Maximum normalized lower left rib lateral acceleration (FIR100 filter)
rlu100	Maximum normalized upper left rib lateral acceleration (FIR100 filter)
pvsax,y,z,r	Maximum normalized pelvic acceleration, all directions and resultant (FIR100 filter)
asa10	Average Spinal Acceleration (*ASA*) over 10-90% peak velocity interval
asa15	Average Spinal Acceleration (*ASA*) over 15-85% peak velocity interval
asa20	Average Spinal Acceleration (*ASA*) over 20-80% peak velocity interval
TTI	Thoracic Trauma Index (*TTI*)

Note: Maxima for variables *latdefln*, *crdefln*, *dmaxn*, *crvmaxn* and *crvdiffn* apply to maximum of respective quantities for lower and upper chest bands. The value of *avdefmxn* is the maximum of spatial average for lower and upper bands.

Average Spinal Acceleration *ASA* is determined by first integrating the lower spinal lateral acceleration *spl180* over time to obtain a velocity signature. The variables *asa10*, *asa15* and *asa20* are then calculated as averages of the slope of the velocity profile over time intervals corresponding to 10%-90%, 15%-85% and 20%-80% of peak velocity.

3.3.1.1 Scaling of Risk Factors

All risk factors with the exception of *ASA* and *TTI* are normalized so that they are nondimensional. Chest deflections are divided by the initial chest width at the elevation of a chest band. Curvature data, having units of reciprocal length, are normalized by multiplying by the initial chest depth at the chest band elevation. Acceleration is scaled using the equal velocity-equal stress formulation described by Eppinger et al. (1984),

$$acc = acc_{nom}\left(\frac{mass}{75kg}\right)^{0.333} \tag{3-3}$$

where acc_{nom} is the unscaled acceleration and *mass* is the mass of the subject in kg. *ASA* is normalized to account for variation in subject age and mass according to the equation

$$ASA = ASA_{nom} * \frac{age}{45} * \frac{mass}{75kg} \tag{3-4}$$

The Thoracic Trauma Index *TTI* is calculated using Eq. 3-1, which includes the influence of subject age and mass. The variables *ASA* and *TTI* have units of g's.

3.3.1.2 Statistical Methods

Logistic regressions for probability P as a function of independent variables $x_1, x_2, x_3, ..., x_n$ have the form

$$P = \frac{e^{b_0+b_1x_1+b_2x_2+....+b_nx_n}}{1+e^{b_0+b_1x_1+b_2x_2+....+b_nx_n}} = \frac{e^{L(x)}}{1+e^{L(x)}} \tag{3-5}$$

with the *logit L* defined as

$$L(x) = b_0 + b_1x_1 + b_2x_2 + ... + b_nx_n \tag{3-6}$$

Forward or backward stepwise logistic regression is used to determine the set of independent variables x_i that are statistically significant. In backward stepwise regression, the full set of risk factors for consideration is specified initially, and the regression process eliminates variables deemed to be statistically insignificant. Forward stepwise regression,

where variables are added consecutively to the set x_i from an initial null set, is used to confirm the results of backwards regression. Statistical significance is evaluated by examining likelihood ratios and related statistics. Goodness-of-fit is assessed by consideration of several statistical measures such as the Hosmer and Lemeshow (1989) goodness of fit $\chi^2_{H\text{-}L}$ and the Goodman-Kruskal (1954) Γ.

Commercial grade statistical analysis tools STATISTICA and STATA were employed for the determination of logistic regressions.

3.3.2 Results

Logistic regressions were performed for each risk factor x_i using age as a confounder variable. Regressions for P(AIS ≥ 3) for deflection-based and curvature-based risk factors, and for *ASA* and *TTI*, are given in Table 5. Statistical significance is assessed by examining the magnitude of -2ln(*lr*) where *lr* denotes the likelihood ratio, a measure of the ratio of the likelihood that the complete model captures the data to that for a model not including the x_i. The larger the value of –2ln(*lr*), the greater is the statistical significance of the model. The value of *p* in Table 5 is the probability associated with the value of –2ln(*lr*) given a Chi-squared distribution, and should be small ($p < 0.05$) for statistical significance.

Table 5. Logistic regressions for P(AIS ≥ 3)

Logit *L* of model for *P*(AIS≥3)	-2ln(*lr*)	*p*	PseudoR^2	χ^2_{H-L}	$P_{H\text{-}L}$	Kruskal Γ
-16.48 + 0.151 *age* + 24.07 *dmaxn*	14.92	0.0006	0.4453	10.59	0.2260	0.7875
-9.94 + 0.111 *age* + 18.67 *latdefln*	11.61	0.0030	0.3467	5.76	0.6737	0.7625
-14.46 + 0.119 *age* + 33.70 *crdefln*	14.96	0.0006	0.4465	11.36	0.1819	0.7750
-12.66 + 0.124 *age* + 44.75 *avdefmxn*	12.92	0.0016	0.3856	12.74	0.1211	0.7375
-38.11 + 0.285 *age* + 2.710 *crvmaxn*	24.73	0.0000	0.7382	1.89	0.9842	0.9500
-15.38 + 0.128 *age* + 1.221 *crvdiffn*	16.85	0.0002	0.5031	4.88	0.7698	0.8500
-1.643 + 0.074 *asa10*	6.61	0.0101	0.1973	10.41	0.2371	0.5625
-1.834 + 0.068 *asa15*	6.49	0.0109	0.1936	5.10	0.7464	0.5500
-1.111 + 0.043 *asa20*	4.36	0.0367	0.1303	8.39	0.3959	0.4500
-8.434 + 0.052 *TTI*	11.50	0.0007	0.3432	5.29	0.7265	0.7500

lr = Likelihood ratio; *H-L* = Hosmer and Lemeshow (1989) goodness of fit measures

Results for Hosmer-Lemeshow goodness-of-fit measures $\chi^2_{H\text{-}L}$ (low for a good fit) and $P_{H\text{-}L}$ (high for a good fit) indicate that the best fits are associated with curvature-based risk factors *crvmaxn* and *crvdiffn*. Values of Kruskal Γ, an independent measure of goodness-of-fit (a larger value implies a better fit), are also consistent with this result.

Table 6 shows results of stepwise backward logistic regression P(AIS ≥ 3) obtained using the STATA computer code. When the initial set of independent variables x_i includes *age* as a confounder variable and all risk factors not having strong cross-correlation, only *age* and *crvdiffn* survive. This provides further evidence that maximum normalized curvature difference *crvdiffn* is the most statistically significant risk factor.

Table 6. Results of stepwise backward logistic regression for P(AIS ≥ 3)

Initial Set of Risk Factors	Surviving Risk Factors
age latdefln crdefln avdefmxn dmaxn crvdiffn spnursn spl100 rlu100 pvsay asa15 TTI	*age crvdiffn*
age crvdiffn spnursn	*age crvdiffn*
age dmaxn crvdiffn	*age crvdiffn*

3.3.2.1 Logistic Model Improvement using Logarithms

As a consequence of the form for the logistic regression, a nonzero probability of injury will result when the risk factors are all zero. Specifically, this probability is given by

$$P(\mathbf{x}=0) = \frac{e^{b_0}}{1+e^{b_0}} > 0 \tag{3-7}$$

Hence, a finite probability of injury will be obtained for zero risk factor, e.g., the undisturbed state. A technique that can be used to improve the fit of the model at low values of risk factor is to apply logarithms to the independent variables in the logit form,

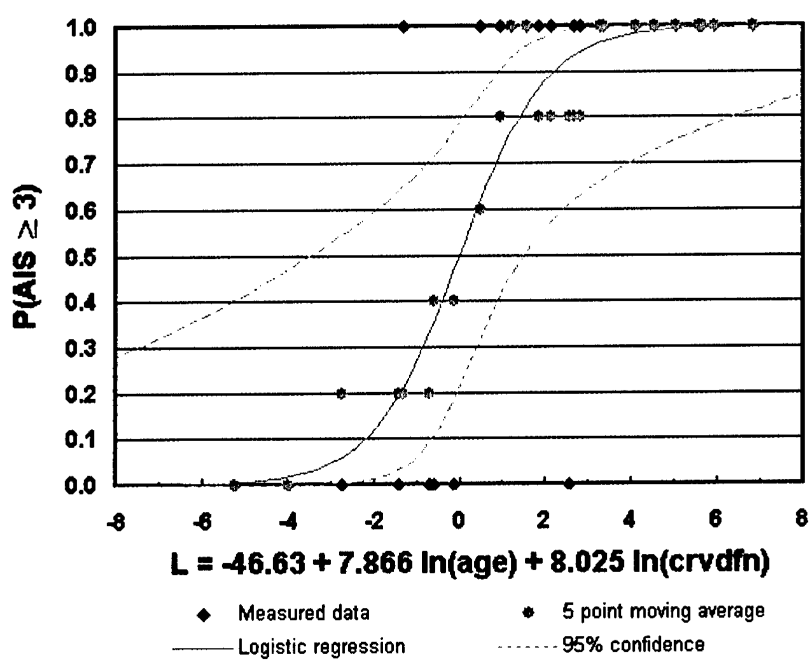
$$L(x) = b_0 + b_1\, ln(x_1) + b_2\, ln(x_2) + \ldots + b_n\, ln(x_n) \tag{3-8}$$

Logistic regressions were performed for all risk factors using the logarithmic form given by Eq. 3-8. The effect of employing logarithms is to slightly improve both the goodness of fit and statistical significance, as shown in Table 7.

Table 7. Logistic regressions with and without logarithms of risk factors

Logit L of model	-2ln(lr)	p	Pseudo R^2	$\chi^2_{H\text{-}L}$	$P_{H\text{-}L}$	Kruskal Gamma
P(AIS≥3)						
-46.63 + 7.866 ln(*age*) + 8.025 ln(*crvdiffn*)	17.91	0.0001	0.5347	5.41	0.7124	0.8750
-15.38 + 0.128 *age* + 1.221 *crvdiffn*	16.85	0.0002	0.5031	4.88	0.7698	0.8500
P(AIS≥4)						
-25.32 + 3.620 ln(*age*) + 5.201ln(*crvdiffn*)	11.89	0.0026	0.3063	5.28	0.7278	0.6735
-9.30 + 0.059 *age* + 0.740 *crvdiffn*	11.68	0.0029	0.3008	4.66	0.7937	0.6531

The logistic regression for P(AIS ≥ 3) with ln(*crvdiffn*) as a risk factor and ln(*age*) as a confounder is illustrated in the following figure. Dichotomous outcomes (0 or 1) for AIS ≥ 3 are also included, in addition to a five point moving average of binary outcome. The moving average is seen to approximate the regression curve, and lies within the 95% confidence bands.



Logistic regression of P(AIS³3) using logarithms of age and maximum curvature difference

3.3.3 Conclusions

Results of statistical analysis show that subject age at death has a significant influence on injury sustained in side impact. The effect of age can be attributed to a change in material properties of bone, with the fracture stress of human bone tissue decreasing with increasing age.

Among an extensive set of risk factors considered, including deflection-based and acceleration-based risk factors, the logistic model for *maximum curvature difference* shows the greatest statistical significance and the best fit to the observed data. In addition, only *age* and *maximum normalized curvature difference* survive as independent variables in stepwise backward and forward logistic regressions.

Probabilistic models based on logistic regression have the property of yielding finite probabilities when all of the independent variables are nonzero. A method that can be used to improve the behavior of logistic regressions for very low values of risk factor is to apply logarithms to all independent variables. Model predictions for zero risk factor (an undisturbed thorax) result in a zero probability of injury using this technique, with accompanying improvements in overall goodness of fit and statistical significance.

Maximum curvature can be envisioned as a function of the maximum stress reached in the thorax, and as such, curvature can be conceived of as a biomechanically-based risk factor for thoracic injury. The same cannot be said of acceleration-based risk factors.

Product 5. Masiello, Paul J. (2002). "Side Impact Rib Fracture Injury Analysis," Injury Biomechanics Research, Proceedings of the Thirtieth International Workshop, Point Vedra Beach, Florida, November 10, 2002.

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4. Head Injury

As part of MRMC-NHTSA relationship, Jaycor developed a biomechanically based, side impact skull fracture criterion; closed head injury data in nonhuman primates was collected, digitized and organized into a visual IISYS database; and a new pressure sensor and associated calibration device were designed and produced.

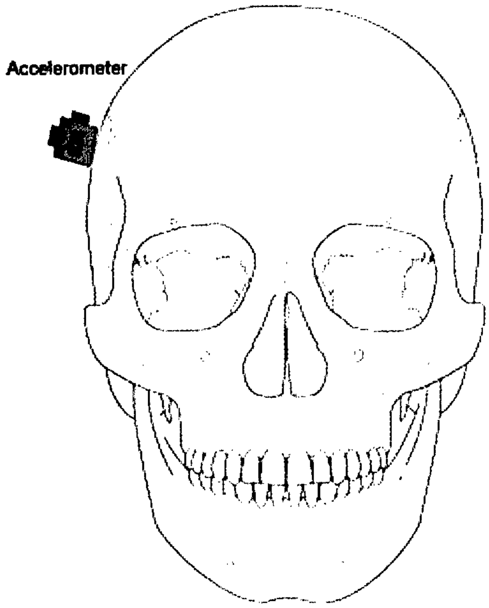
4.1 Biomechanically Based Skull Fracture Correlates

Biomechanically based criteria for side impact-induced skull fracture, expressed in terms of measurements by an anthropomorphic test device, were developed. In collaboration with the Medical College of Wisconsin, new side impact drop tests of Post Mortem Human Subjects (PMHS) were performed. The MCW tests were combined with PMHS side impact tests from the open literature to form a skull fracture database containing data for a wide range of impact surface curvature and hardness. Drop tests were conducted using the 50^{th} percentile male Hybrid III and 5^{th} percentile female SiD2s headforms to generate both kinematic and dynamic data corresponding to the PMHS tests. Time histories of force, acceleration, and impact area were measured. To obtain biomechanical data, skull strain was calculated by a finite element head model containing a scalp; a homogenous brain; and most importantly a three-layered skull with an inner table, diploe layer, and an outer table. Logistic regression analysis was used to generate correlations between the previously observed fractures of cadaver skulls, the parameters measured in the headform tests, and the calculated tensile strain.

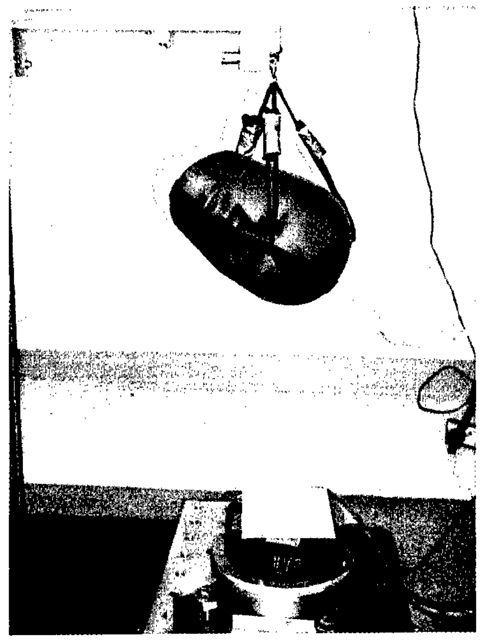
The results of this effort are side impact Skull Fracture Criteria (SFC) for use in automotive crash worthiness testing. SFC is the average acceleration over the HIC time interval measured by the dummy headform. The resulting side impact criteria at 15% probability of skull fracture are:

SFC < 130 g for $50^{\%}$ male Hybrid III, and

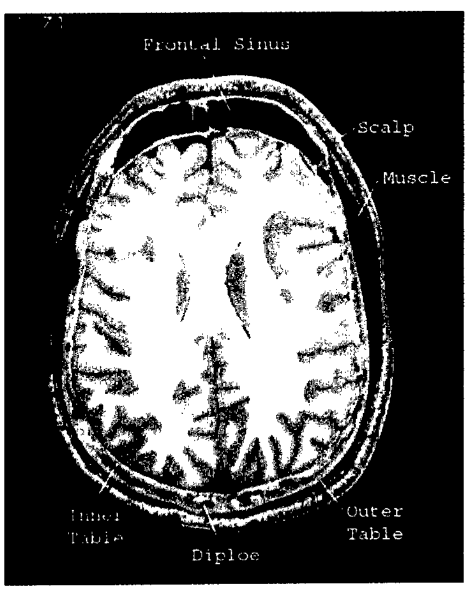
SFC < 145 g for 5% female SID2s.

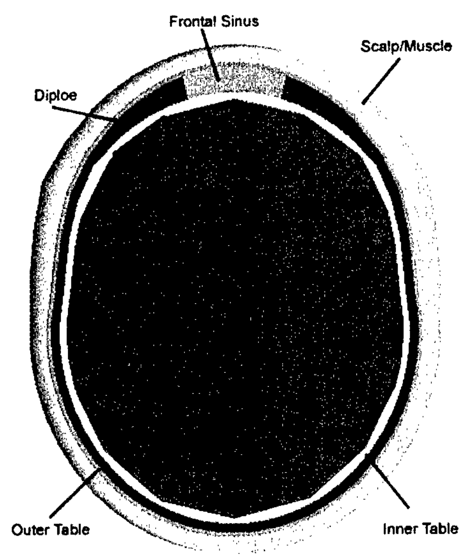


PMHS Instrumentation

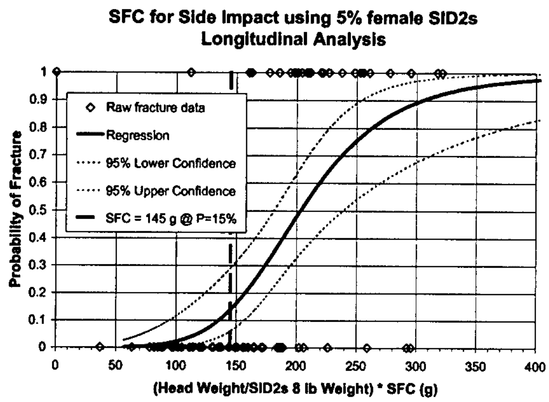


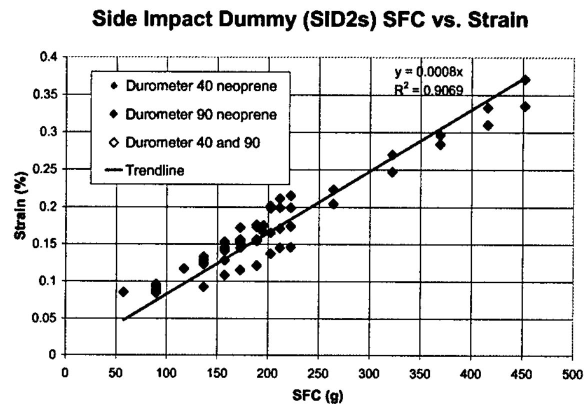
Drop Test Setup





Cross Sections of human head and corresponding finite element model

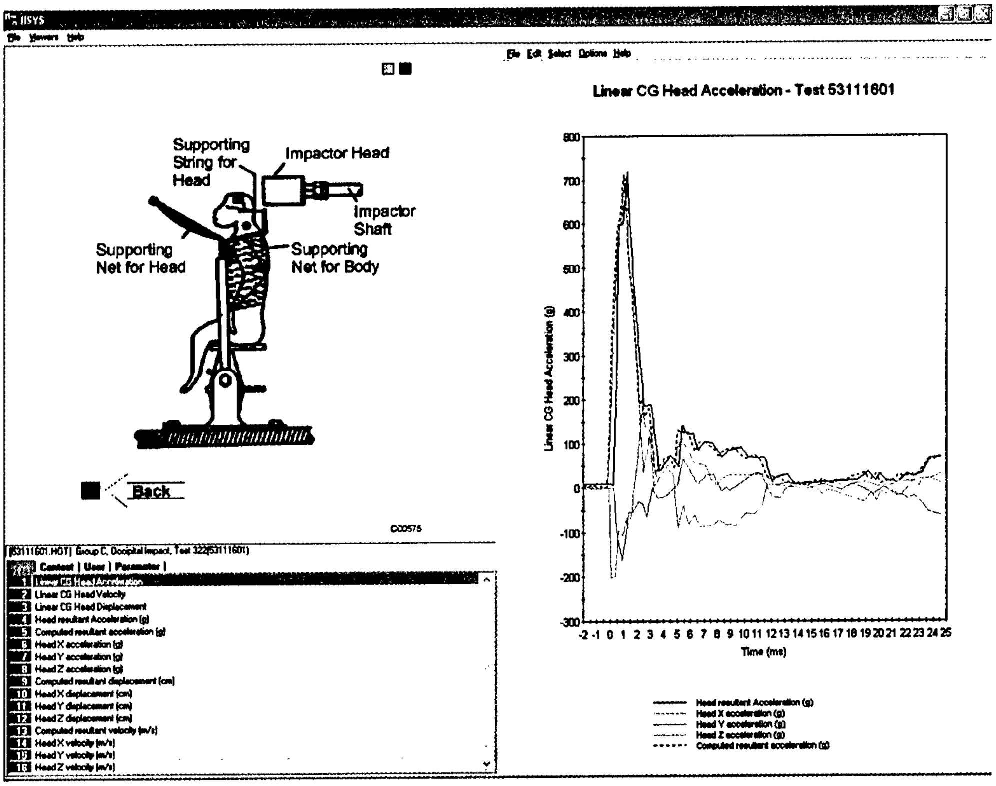




Product 6. Vander Vorst, M.J, Stuhmiller, J., Ho, K., Yoganandan, N. and Pintar, F. (2003), "Statistically and Biomechanically Based Criterion for Impact-Induced Skull Fracture," Proceedings of the 47th AAAM Annual Conference, Lisbon, Portugal.

4.2 JARI Closed Head Injury Database

In the late 1970's and early 80's, the Japanese Automobile Research Institute (JARI) conducted an extensive series of studies on closed head injury due to external forces on the heads of subhuman primates. Tests were done over a wide range of linear and rotational head accelerations with outcomes ranging from no injury to concussion to hematomas, hemorrhages, and contusions. Data taken included input forces, head acceleration, heart rate, respiration rate, movies, photographs and pathology. All of this data was digitized, summary data was placed in a Microsoft Access database and an IISYS session was developed. This data will be the basis for developing risk factors for closed head injury.

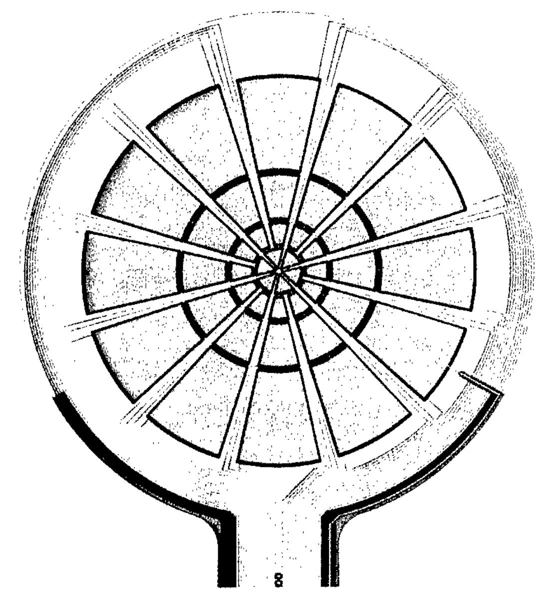


Screen from JARI IISYS Session

Product 7. Vander Vorst, M.J and Long, D.W. "JARI IISYS Session" (June 2003)

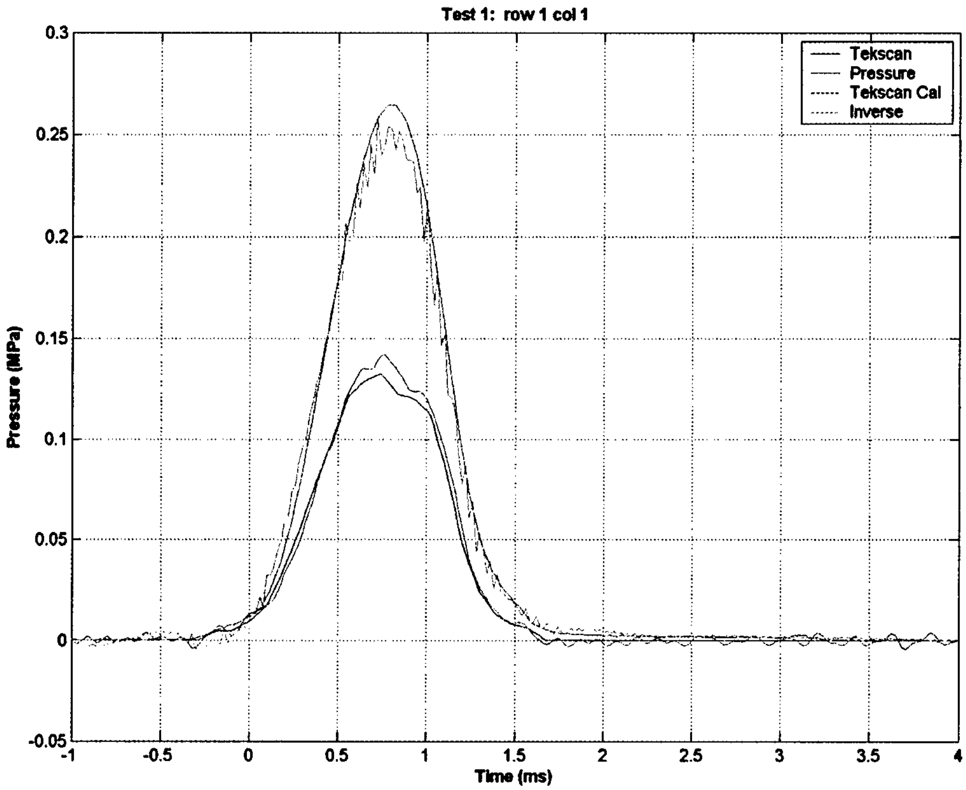
4.2.1 Pressure and Impact Area Instrumentation

Jaycor developed a new Tekscan pressure sensor, the Bulls Eye sensor, for use in impact tests. This sensor has four concentric rings of cells with small cells in the interior rings to resolve the high pressures at the point of impact and larger cells in the exterior rings where the pressure is lower. TekScan instrumentation measures the transient pressure distribution at a sample rate of up to 10,000 Hertz over 42 cells. Calibration of TekScan sensors using TekScan's static methodology produced total forces, as measured by TekScan, that were far different from those measured by a force gauge. Jaycor developed a test device and associated software to calibrate



Bulls Eye Tekscan Sensor

each sensing element under a dynamic load. Using Jaycor's calibration method and data interpretation software, the TekScan instrumentation now measures dynamic pressure



distributions during an impact that agree with force gauge measurements.

Product 8. Vander Vorst, M.J., Bulls Eye Tekscan sensor, (April 2003)

Product 9. Vander Vorst, M.J., Dynamic calibration test device for Bulls Eye sensor (May 2003).

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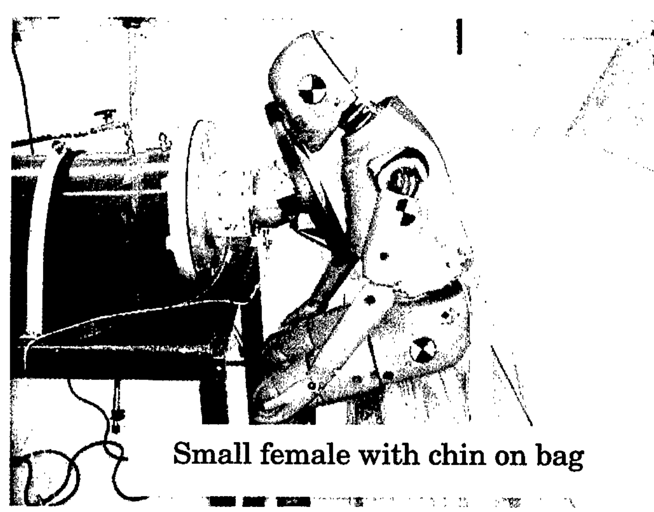
5. Air Bag Dynamics

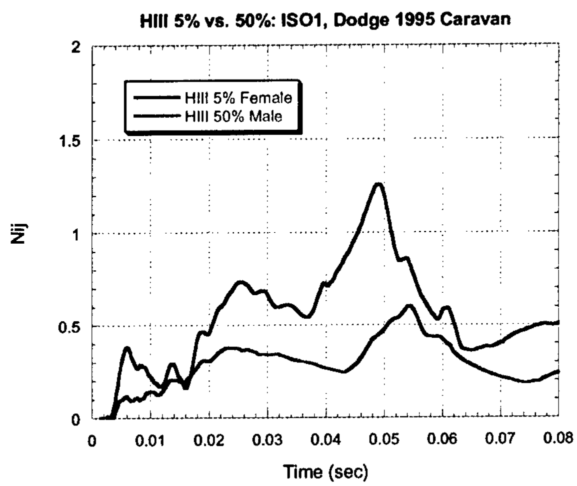
As part of the MRMC-NHTSA cooperative research, Jaycor continued to study airbag load on occupants at close proximity and develop new methods to measure contact load. The current work focuses on head/neck and chest responses. The pneumatically driven Airbag Test Simulator (ATS) has been demonstrated to be a highly useful and efficient apparatus for studying airbag loads and developing new instrumentation methods. The significance of using the ATS is that repeatable tests can be carried out with accurately controlled inflation without using the fleet inflators. This ability to generate repeatable data is important since it is well known that airbag tests tend to produce data variability, making it difficult to conclude phenomenological observations. Finite element airbag dummy interaction model simulations were also carried out.

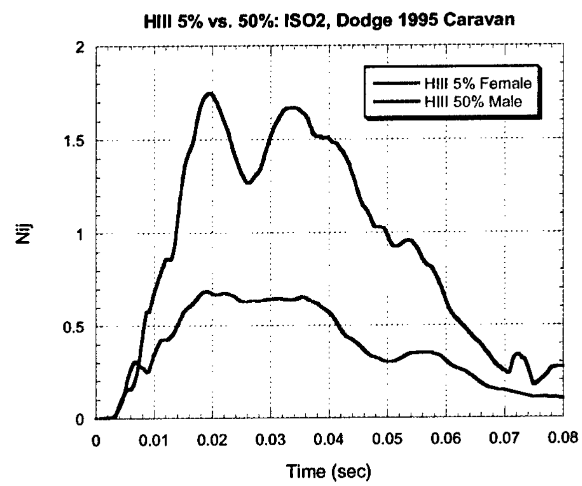
5.1 Airbag Load Sensitivity Study



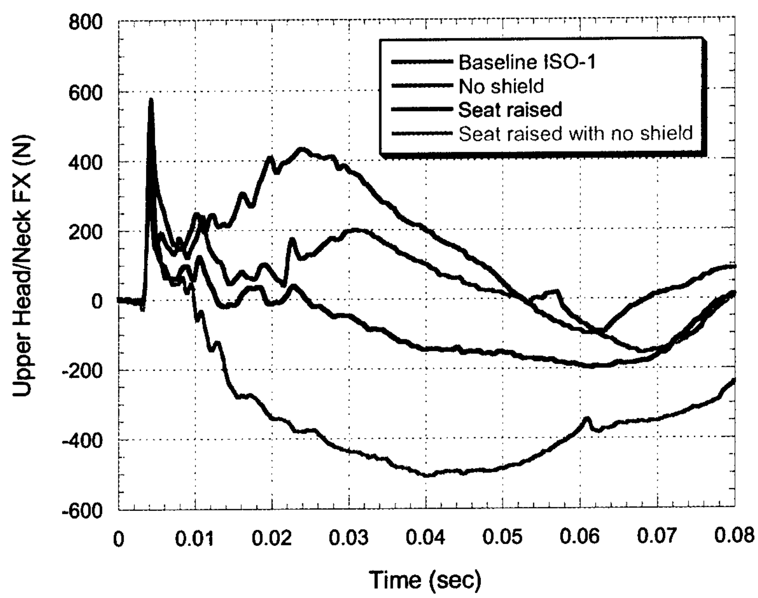
Small female with chin on bag

Smaller occupants are more vulnerable to out-of-position (OOP) airbag loads. ATS tests confirm a higher head/neck injury risk for smaller drivers at OOP conditions. For the selected bag as tested without bag cover, the Nij for the small (5th percentile female) dummy is twice as high as the mid-size (50th percentile male) dummy at both ISO-1 (chin on bag) and ISO-2 (chin on wheel) positions. Nij is a normalized metric based on head/neck tensional force and moment, and injury occurs when Nij is greater than 1. A smaller dummy will tend to produce higher Nij due to higher head/neck loads that are also normalized by lower injury tolerances. The optimal reduction of OOP load injuries to small occupants at low speed without compromising crash protection for large occupants at high speed requires accurate understanding of where the load comes from. This challenge is compounded by the sensitivity of airbag load to many parameters.



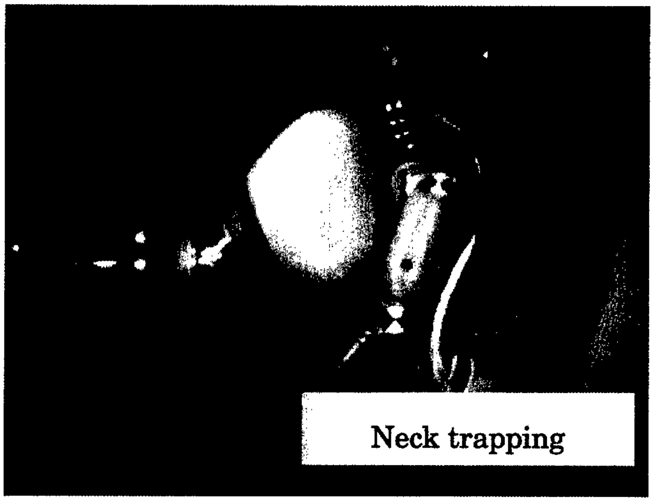


Nij comparison between mid-size and small dummies



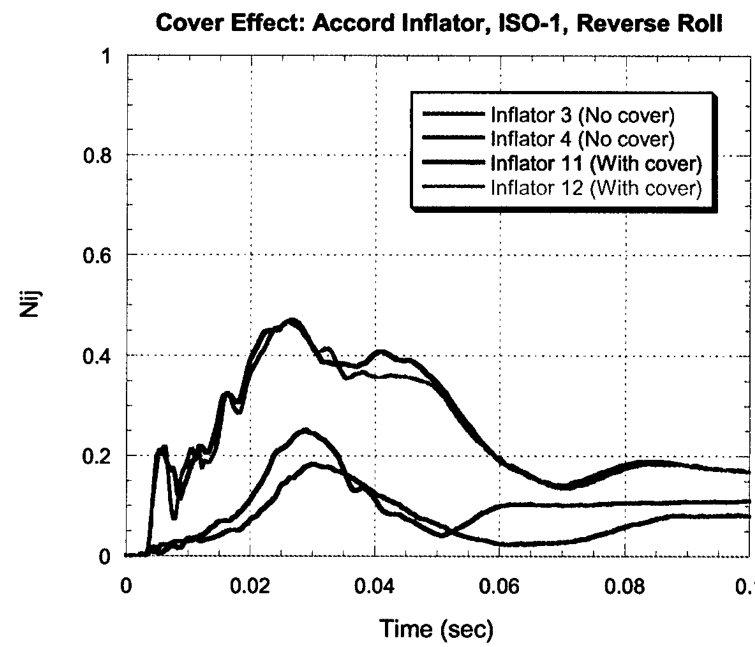
Sensitivity studies using the mid-size dummy show that the head/neck responses are sensitive to small change of test conditions. The baseline test shows the head/neck is subjected to the typical punch out load from 0-10 ms, followed by the membrane phase load from 10-60 ms, and the head stays mostly in flexion with positive head/neck shear. By just removing the neck shield, the head/neck shear force decreases by a factor of 2 during the membrane phase when compared to the baseline response. The neck shield sensitivity was evaluated because its biofidelity is still an issue under debate. If the neck shield is kept on but the seat is raised by only 1.5", the head/neck shear becomes negative after 20 ms, which means the moment will change from flexion to extension. Keeping the seat raised by 1.5" and also removing the neck shield, the head/neck shear becomes strongly negative after 10 ms, with the neck subjected to strong extension.

This tendency of the neck to switch from flexion to extension when the seat is raised by 1.5" is due to neck trapping. Neck trapping occurs when the leading edge of the bag is trapped at the chin/neck cavity, allowing the inflating bag to pry the head from the neck that can result in strong neck extension. It was also observed by other investigators that



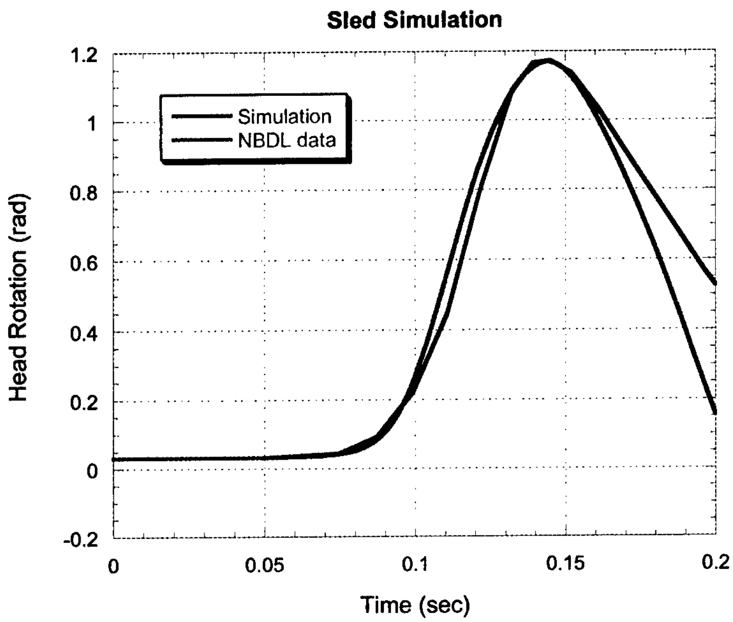
neck trapping could occur sometimes even when the dummy is at the baseline position for some airbags. The neck shield has been recommended for use with the Hybrid III to help prevent neck trapping but the biofidelity of neck trapping is still an ongoing debate; since some believe the smoother human neck contour should prevent neck trapping. On the other hand, it seems neck trapping can still occur when the bag is allowed to deploy right into the chin/neck cavity, which is the case when the dummy is raised by only 1.5" as observed in our tests. This strong sensitivity of head/neck response to the dummy elevation opens the question of whether the current test standard has identified the "worst" occupant position for new car assessment program (NCAP) testing. Current DOT test regulation only specifies one dummy position for NCAP crash tests, and it is unclear if this even adequately covers the variability of steering wheel and seat configuration between cars. It is also highly likely that the occupant position can easily vary by 1.5" in field conditions.

The bag cover and steering wheel was found to actually increase the airbag load on the dummy. For a selected depowered bag at the chin-on-bag position, the bag cover increases the Nij by a factor of two. The main reason is that the opening process of the bag cover lowers the bag deployment direction to the neck. With no bag cover, the bag first hits the chin and produces neck flexion. With the cover, the bag comes out at a lower angle and hits right at the chin/neck cavity to produce neck trapping, resulting in strong head/neck shear, extensional moment and Nij. Furthermore, after the bag cover is flipped open, it rests on the steering wheel and provides more rigid backing for the inflating bag like an enhanced shape-

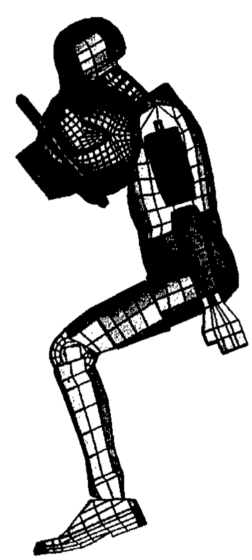


charge effect that increases the airbag load on the dummy. On the other hand, the airbag load is reduced when the steering wheel is removed. These results indicate the control of airbag load depends on many factors that need to be optimized to minimize OOP hazard without compromising crash protection for large occupants.

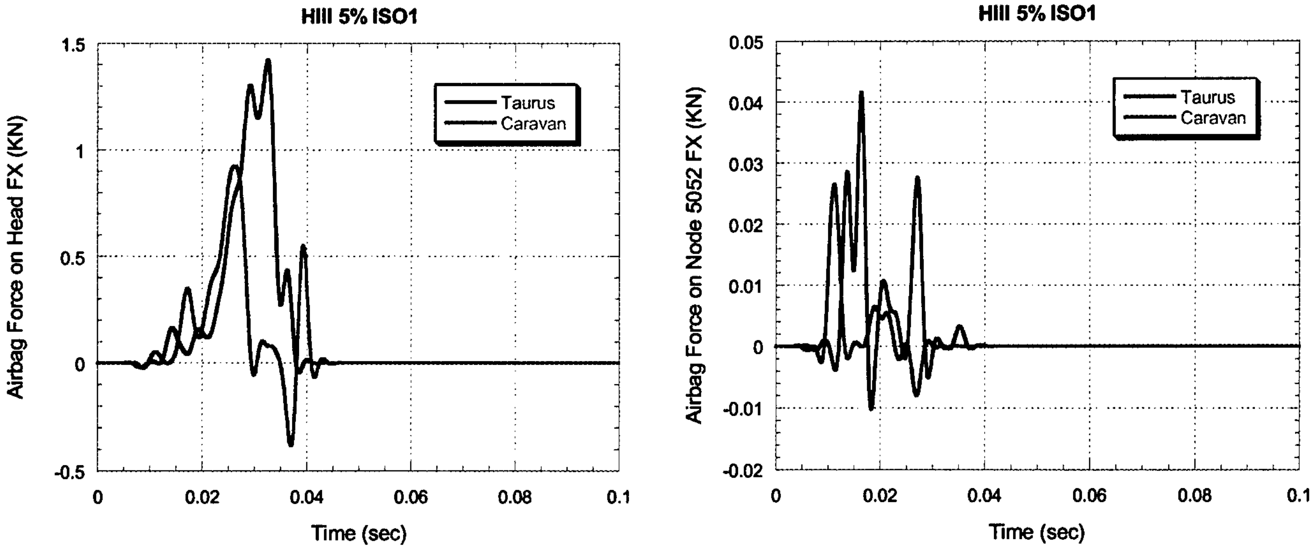
A finite element model was constructed using the LS-DYNA software to simulate the airbag-dummy interaction. The baseline 50th percentile male dummy model was selected from the LS-DYNA library. The dummy model has a full Hybrid-III deformable neck and thorax. The rest of the extremity components were taken as almost "rigid" but fully articulating components. Since the current focus is on the head/neck response, the head/neck model was first validated against the benchmark Naval Biodynamics Laboratory +Gx sled test data. The simulation was carried out by specifying the T1 acceleration data as input. The calculated head rotation dynamics agrees well with the data. This provides credence for using the model to study head/neck responses subjected to airbag load.



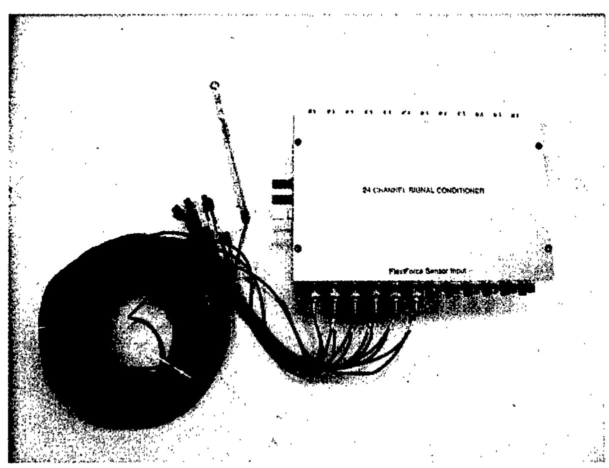
An airbag folding model was constructed using the INGRID software. The proper set up of the airbag membrane elements at the folded condition is an important step. The correct specification of the gap tolerance between the bag surfaces and the curvature of the folding is critical to prevent numerical errors during the bag unfolding process. The airbag also has leak holes. The model includes a steering wheel and the airbag module with cover. The airbag is deployed by specifying the gas inflation rate and temperature. A uniform bag pressure is assumed during inflation.



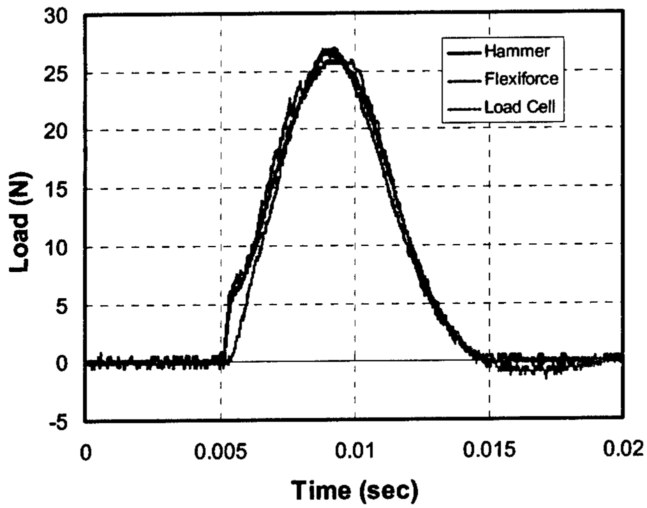
A series of exploratory calculations was carried out for two airbags. The calculation results show



reasonable trends, with the stronger (Taurus) bag producing stronger dummy responses than the weaker (Caravan) bag. Besides calculating the dummy response, the finite element simulations provide valuable external load information, such as for the entire head, as well as for a specific location, such as at the chin. These data, however, are still not available from airbag tests due to the complexity of measuring the external airbag contact load on a dummy with compliant skin. These are the critical missing data needed to fully understand how the load is generated and distributed to guide the improvement of airbag design. The validation of the finite element model simulations requires the collection of dummy contact load data.



A methodology of measuring the external contact load on a dummy was developed using thin film FlexiForce sensors. Made by TekScan, the FlexiForce sensors are individual (single) sensors that can be distributed over an area to measure load distribution. The use of distributed single sensors avoids the complication of mounting flat film sensors over a surface with double curvature. A 24-channel signal conditioner was constructed to take synchronized data from 24 FlexiForce sensors. Since the sensor outputs analog signals, there is great flexibility of controlling the sampling rate as desired, and 10 KHz per sensor can be collected using the signal conditioner and the high speed data acquisition system.



A technique was developed to overcome the difficulty of measuring surface load on the compliant dummy skin by mounting the FlexiForce sensor on top of a small thin rigid backing surface like a "smooth penny" that can be easily glued on the dummy skin. An extensive series of calibration tests was conducted to validate this technique by testing various kinds of sensor backing material and thickness. Calibration tests show that the sensor backing "penny" can be about 0.04" thick with 0.75" diameter made out of aluminum or steel. When the FlexiForce sensor is mounted on the "smooth penny" on top of the compliant skin, the FlexiForce output matches closely with the outputs from the calibration hammer and the load cell. Otherwise, without the backing penny, poor data is collected when the FlexiForce sensor deforms with the skin when subjected to external load.

This methodology based on FlexiForce sensors is being evaluated using airbag tests. A number of low range sensors are glued on the small female dummy. The dummy is subjected to various airbag loads. The contact load data will be correlated with the dummy response data and also used for model validation. This process is necessary to truly understand airbag load dynamics and dummy responses. Tests will also be conducted for the mid-size dummy and a range of THOR dummies. Upon validation, NHTSA plans to use this contact force measurement method for measuring seat belt loads as well as other contact loads for crash tests.

Product 10. Chan, P., Ho, K., and Lu, Z, "Evaluation of Hybrid III and THOR Dummy Head/neck Responses to Airbag Load at Close Proximity," paper presented at 2003 International IRCOBI Conference on the Biomechanics of Impact with AAAM, September 24-26, 2003, Lisbon, Portugal.

Product 11. 24-Channel signal conditioner for FlexiForce sensors

Product 12. Chan, P. and Lu, Z., "Development of Methodology to Measure Airbag Contact Load," paper to be presented at the 31st International Workshop on Injury Biomechanics Research sponsored by NHTSA, October 26, 2003, San Diego, CA.

Product 13. Lu, Z. and Chan, P., "Out-of-Position Airbag Load Sensitivity Study," Paper submitted to SAE 2004 World Congress, March 8-11, 2004, Detroit, Michigan.

Product 14. Chan, P. and Lu, Z., "Laboratory Study of Hybrid III and THOR Dummy Head/Neck Responses to Airbag Load at Close Proximity," paper submitted to SAE 2004 World Congress, March 8-11, 2004, Detroit, Michigan.

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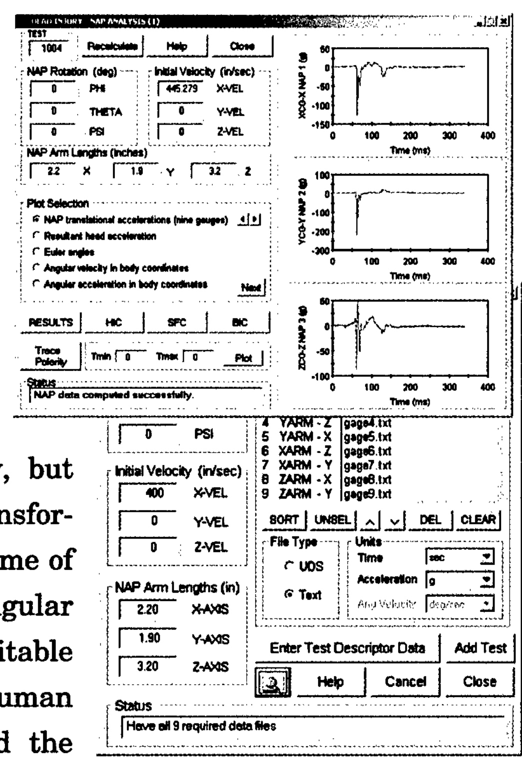
6. SIMon Computer Code

6.1 Background

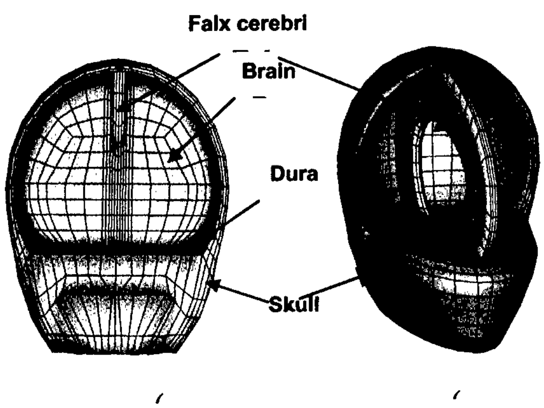
The SIMon (*Simulated Injury Monitor*) computer code, a next generation (G2) tool for the assessment of bodily injury resulting from automobile collisions, was developed by Jaycor under NHTSA sponsorship. The objective of SIMon is to provide an integrated and simple-to-use mechanism to utilize recent advancements in computational techniques that can be employed to simulate human injury response. In light of recent advances in computer hardware, the idea of detailed injury assessment in real-time can be brought much closer to reality. SIMon provides a convenient interface between a biomechanics researcher, appropriate test data of interest, and invocation of a detailed mathematical model for simulation of impact injury to a specified body region. Presently, the focus of SIMon is on head injury, but other models addressing the neck, thorax and lower extremities are planned for the future.



At present, the most useful feature of SIMon is a model to process Nine Accelerometer Package (NAP) test data, as well as data recorded by angular velocity (AV) sensing devices (e.g., MHD sensors). NAP devices allow measurement of nine linear accelerations along three orthogonal directions, for the purpose of computing accurate and reliable values for rotational velocities and accelerations. These quantities play a pivotal role in the assessment of head injury. In the case of AV sensing devices, the angular velocity is measured directly, but rotational acceleration is still desired, as well as transformation from body-fixed coordinates to an inertial frame of reference. The resulting linear and rotational angular velocities constitute data for the construction of suitable load curves for a finite element model (FEM) of the human brain. This model can be invoked by SIMon, and the progress of the FE calculation, as well as graphical results, can be displayed by SIMon in real-time.

SIMon is designed to access a database either supplied by NHTSA or constructed and maintained by a user with the help of SIMon dialogs. Familiarity with database tools or software is not required. The user can easily add a test to the database by a simple drag/drop operation, referencing his/her data files from the Windows Explorer. Content of database fields of interest (such as the test number, date, test performer, etc.) can be entered directly from within SIMon dialogs. Once added, a user's test can be deleted from the database, or its database fields can be edited. Assembly and maintenance of the user database is managed entirely by SIMon. The data files that are dragged/dropped to define a test are copied into a special storage area maintained by SIMon. Hence, the original data files can be deleted at any time.

Injury assessment is made by viewing the graphical and printed data generated by SIMon for the particular model invoked. Printed output data are written to disk files saved by SIMon in an ordered directory structure.



In November 2001, SIMon 1.0 Beta was released at an annual Stapp conference workshop, and over 50 CD-ROMs were distributed to domestic and international members of the biomechanics community. The initial version of SIMon was well received. Since the initial release, an additional 20 CD-ROMS have been distributed to new users. A mechanism for user feedback and code support has been established by NHTSA and Jaycor.

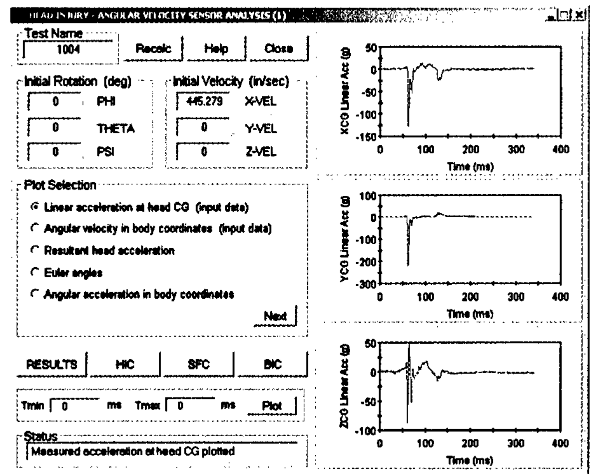
Product 15. SIMon Simulated Injury Monitor Version 1.0 Beta Computer Code, Jaycor, Dr. Paul J. Masiello, November 15, 2001. Released and distributed at 2001 Annual Stapp Conference, San Antonio, Texas.

Product 16. Bandak, F.A., Zhang A.X., Tannous, R.E., DiMasi, F., Masiello, P. and. Eppinger, R., "SIMon: A Simulated Injury Monitor; Application to Head Injury Assessment," 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Amsterdam, Netherlands, June 4-7, 2001.

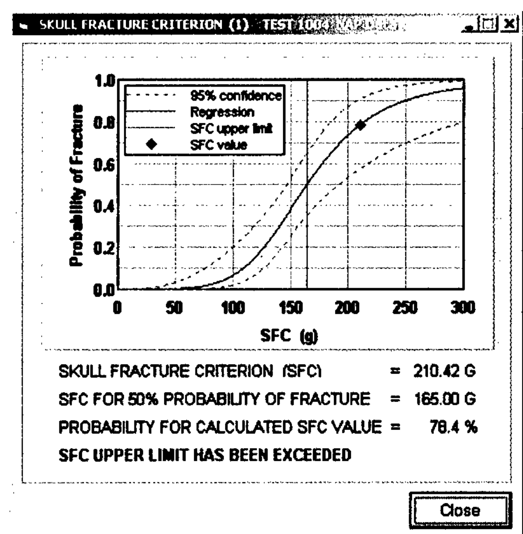
Product 17. Kan, K.K. and Masiello, P.J., "Implementation of Euler Angles in the NAP Computational Model," Jaycor Technical Report J2997.104-02-169, February 2002.

6.2 Progress in FY03

During FY03, development and support of SIMon continued under NHTSA sponsorship, and several new features and code enhancements were made available in a new version of the code, SIMon 2.0. Specifically, the list of tasks addressed include:



- Enhancements to processing of Angular Velocity (AV) sensor data, including use of arbitrary unit systems.
- Addition of a dialog to output the Skull Fracture Criterion (SFC).
- Ability to initiate several FEM head calculations simultaneously, and to track their progress.
- Correct deficiencies and limitations in user's ability to edit existing test data.
- Allow up to 12 character user test names, resulting in the ability to distinguish between different occupants of a vehicle, or different calculations for the same test.



- Ignore portions of NAP and AV traces prior to time zero.
- Addition of a commercial grade Windows compatible Help system.
- SIMon was tested under the Windows XP operating system.
- Enhanced plotting capabilities. Any plot in a SIMon dialog can be double-clicked to obtain a plot in a separate window. Plot attributes can then be changed easily by means a stand-alone plot interface, developed separately and supplied with SIMon.
- Provide for display of real-time output from finite element calculations in progress.
- NAP data consistency checker provides user checks of the integrity of the NAP source data. Sign reversals in individual traces can be identified and corrected.

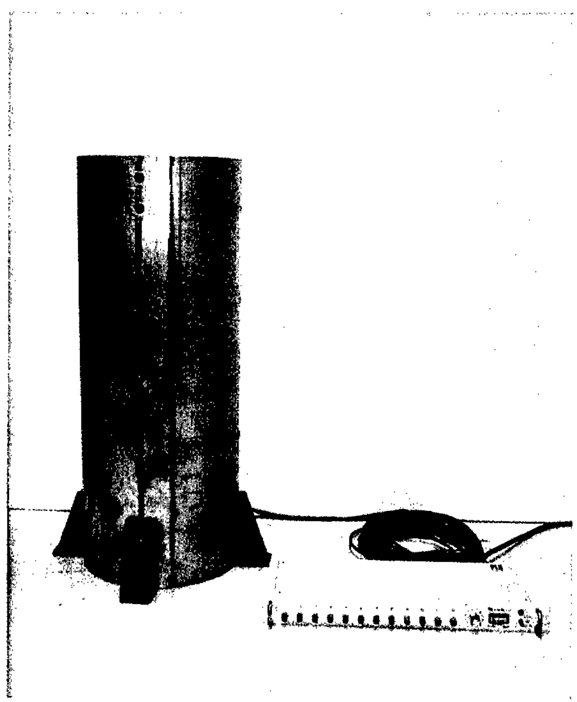
- Provisions for a multiple finite element model capability. The standard SIMon model is that of a Hybrid III crash dummy for the 50 percentile male. Multiple models might constitute different size models of the same crash dummy, or models of different body regions. A rigid skull model is presently employed by SIMon in the NAP data consistency check.
- Replace the present FEM of the head with a refined model, to include a more accurate description of material for brain tissue (performed in conjunction with NHTSA and Livermore Software Technology Corporation).
- Perform final testing and packaging for a new SIMon release to be distributed at the STAPP conference in October 2003.

Product 18. SIMon Simulated Injury Monitor Version 3.0 Computer Code, Jaycor, Dr. Paul J. Masiello, October 26, 2003. To be released and distributed at 2003 Annual Stapp Conference, San Diego, California.

7. Thermobaric Weapon Effects

7.1 Lightweight Blast Test Device

There is a growing need for assessment of blast injuries in urban warfares for troop protection against small charge explosions but involving thermobarics inside structures. To facilitate easier use and handling, a lightweight blast test device (BTD) was designed and constructed using aluminum with internal stiffeners. The design was based on finite element model simulation using 3 lb C4 charge at 4 ft standoff and 1.5 ft above ground, which produces a peak reflected pressure of 1012 psi. The lightweight BTD is about 50 lb, in contrast to the current one that weights 90 lb. The lightweight BTD has the same dimension as the current one, which is 30 inch long with 12-inch diameter. The identical PCB Piezotronics pressure gauges are mounted at the same locations, and the same signal conditioners are used. The lightweight BTD is expected to meet most of the current field test needs with easier handling. The heavy BTD is still available for severe blast test conditions.



7.2 DRDC Test Support

Per MRMC approval, three lightweight BTDs with signal conditioners were delivered to Defence R&D Canada (DRDC) – Suffield with documentation. DRDC requested the use of the BTDs to evaluate blast injury risks to their troops being deployed to Afghanistan and other peace keeping missions. Various tests in bunker and trench configurations will be conducted for a range of weapon warheads, including thermobarics. A range of BTD positions for various threat conditions will be explored, and the lightweight BTD will facilitate the moving of the BTD for parametric studies. The tests will be conducted at the Northern Light test site. For their upcoming tests in September, Jaycor will carry out INJURY calculations using the BTD data collected by DRDC and provide the blast injury results to DRDC. DRDC has inquired about potential field support from Jaycor that will be considered on a case-by-case basis.

7.3 Blast Working Groups

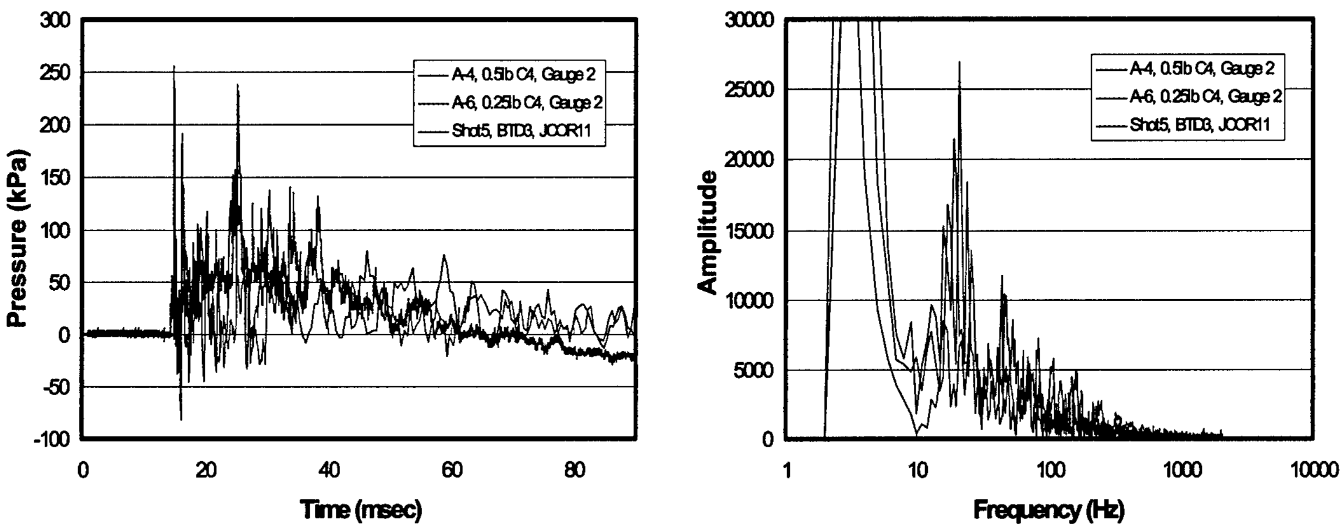
Jaycor participated in the Blast Waveform Working Group organized by the Defense Threat Reduction Agency (DTRA) and the Blast Metric Working Group organized by the US Army SBCCOM, Natick Soldier Center (NSC). A total of at least 7 meetings were conducted, including the closely related US-UK Novel Explosives IEA meetings and the Northern Light Test meeting. The working groups were formed to primarily investigate whether thermobaric explosives lead to enhancements of blast lung injury. Of the two, the Blast Waveform Working Group emphasizes more on the characteristics of the pressure-time history, while the Blast Metrics Working Group sets out to identify the metrics that can predict lung and other injuries due to blast. However, the two groups are closely related, and the presentations and discussions in the two working groups were often similar.

Our participation in the working groups was to bring the MRMC experience in blast lung injury to the research community and to examine the applicability of INJURY to thermobaric explosives. In the meetings, we reviewed the previous work on lung injury from the standpoint of energy transfer to the lung, showing that the work done on the lung is a measure of the energy of the pulmonary compression wave that leads to injury. Therefore, we explained that the work done is the metric for the blast lung injury, which is validated against the statistical analysis of the animal injury data in the MRMC database.

The participation with the user and research community has provided opportunities to correct misinformation and improper use of the INJURY code with the BTD. It was discovered that some users who had earlier versions of INJURY took liberty to just using the incident pressure to predict lung injury and also erroneously ignored the pressure input beyond the A-duration. Results were then presented as predictions from the INJURY code. There is also misunderstanding on how a rigid cylindrical BTD can serve as a lung surrogate to measure lung injury (or response), drawing contrasts to other surrogates such as the British Pig Rig and the Gelman. We made presentations to explain that the BTD is used to collect pressure load data as inputs to INJURY for calculation of probabilities of lung injuries, and the entire methodology has been biomechanically and experimentally validated.

To address the concern of the validity of INJURY for thermobaric waveforms, analysis was carried out to compare the Blossom Point test waveforms with the MRMC conventional blast waveforms. In the Blossom Point Tests, we had previously seen that the pressure-time histories vary only moderately with explosives (from conventional to thermobarics), but drastically with location. Therefore, the thermobaric pressure waves are actually dominated by the geometry of the structure. We examined the complex waves in the MRMC

BOP database and found examples of pressure-time histories that are similar to those obtained in the Blossom Point tests with thermobaric explosives, including the spectral contents. This waveform similarity confirms that INJURY has been validated against waveforms similar to those produced from the thermobaric charges.



Similarity of C4 complex waves in MRMC database (red and green) with thermobaric data in Blossom Point tests (blue)

Analysis of available thermobaric waveforms generally indicates they are slightly to moderately stronger than conventional charges based on equal weight basis, such as having higher impulse and stronger second peak. A series of INJURY calculations were carried out with inputs from BTD data, wall gauge data as well as (third party) computational fluid dynamics results for a range of thermobaric charges. The overall results show that thermobaric charges produce slightly or moderately higher probabilities of blast lung injures than conventional charges. More importantly, INJURY responds differently with good phenomenological basis when the waveforms are different. Nevertheless, very limited close range thermobaric tests using either the BTD or animals have been conducted in the US.

7.4 St. Petersburg Data

The widely circulated impression that thermobarics can greatly enhance lethality is primarily based on the recent test in St. Petersburg. We analyzed the data presented in the St. Petersburg report when it became available to us. Based on the St. Petersburg test, the dramatic enhancements effects are confined only to small animals, i.e., rats and rabbits. On the other hand, the enhancements of lethality are quite small for large animals, i.e., pigs. It is well known that only large animal lung injury data can be scaled to humans. Tests were

conducted both in the open and inside a structure. Some animals were tested with a very simple metal ballistic vest (BV) wrapped around.

Distance from the Blast Epicenter, m	Degree of Contusion Injury Resulted from the Blast Wave							
	Condensed Explosive				Low Density			
	In the Open, 5kg		Inside the Structure, 1kg		In the Open, 5kg		Inside the Structure, 1kg	
	Bare	BV	Bare	BV	Bare	BV	Bare	BV
1.5			IV (1)	III (1)			V (1)	IV (1)
2.0	V ()		III (3)	III-II (3)			III (3)	II-III (3)
2.5			II (2)				II (2)	
3.0	IV (1)				V (1)			
3.5	IV (1)	III (1)						
3.9	III (2)	II-III (2)			III (2)	II (2)		
5.0	II (2)				II (2)	II (2)		

St. Petersburg pig injury test results. Roman numerals indicate lung injury levels. Numbers in parentheses indicate number of animals tested. (Taken from Tiurin et al, 2000)

The data shows only a slight increase of injury due to thermobaric (low density) charges. For the tests inside the structure, only the tests at 1.5 m indicate an increase of injury by one level when condensed (conventional) explosive is changed to low density charge, but only one animal was tested in each case. The rest of the tests inside the structure show the same injuries between the two explosives. Likewise, for the open field tests, only one test at 3 m indicate an increase of injury by one level from condensed explosive to low density charge, and again only one animal was tested in each case. The rest of the tests shows identical injury levels between condensed explosive and low density charges. Therefore, the data indicates at most a slight increase of injury due to thermobaric charges at very close standoff but with poor statistical confidence due to the small number of animals tested.

The St. Petersburg test data are consistent with the INJURY predictions for the Blossom Point Test data; namely, thermobaric charges only slightly increase the level of lung injury. No data has been found to substantiate the claim that thermobarics dramatically increase the probability of blast lung injury. These findings are also consistent with the waveform analysis results that do not show very peculiar behavior in the thermobaric charge waveforms.

Product 19. Kan, K.-K., K. Ho and Chan, P. C. (2003). "Use of INJURY on Thermobaric Blast Waves," Jaycor Report J3193-03-199.

Product 20. Lightweight Blast Test Device.

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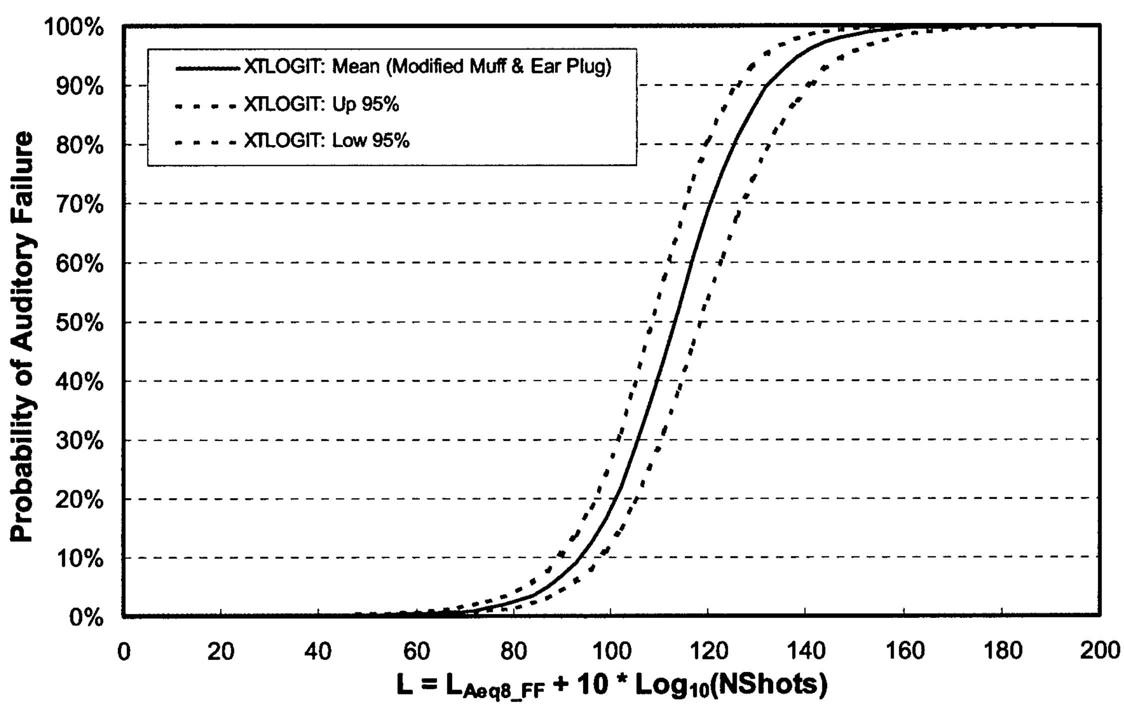
8. Impulse Noise Injury

As part of the NHTSA-MRMC joint cooperative research, we further analyzed the BOP impulse noise data to provide guidance for NHTSA in the assessment of airbag noise injuries. Our previous work in analyzing the BOP data was for the purpose of evaluating the current injury criteria with single hearing protection. For airbag noise application, however, a criterion for unprotected ears is needed. Our previous work indicated that the LAeq8 criterion using A-weighted energy was the best correlate among the NATO standards for assessing noise injury with hearing protection. The MRMC chinchilla data for unprotected ears also shows A-weighted energy is a better correlate than the peak-based correlates, such as the MIL-STD. It seems that LAeq8=85 dB is a reasonable criterion for unprotected ears. The validation effort shown by the French proponents, however, has been quite limited with inadequate statistics, especially for exposures at the high level range. We carried out an analysis to evaluate the LAeq8 criterion using the BOP human data.

The key is to derive an equivalent freefield noise level for injury correlation. For the modified muff test (in freefield and in bunker), the undermuff pressure was analyzed to calculate the LAeq8 level, which was assumed to be at the ear canal entrance. Open literature data show that the SPL at the ear canal entrance can be about 15 dB higher than freefield for the frequency range from 1.5-5 kHz, and lower for other frequencies. The BOP data show that 15 dB SPL corresponds to about 12.8 dBA. Therefore, the undermuff LAeq8 level was reduced by 12.8 dBA to produce the equivalent freefield level. For the earplug



tests, the procedure proposed by Dancier et al of subtracting the freefield pressure by the insertion loss (IL) was followed to calculate the equivalent freefield exposure with the earplug since the IL data were available. Pooling the undermuff and earplug data together, the logistic correlation shows that the L(95,95) for LAeq8 is 83.34 dB, which is slightly lower than the proposed 85 dB.

Because of the assumptions involved, our analysis may still be too qualitative, but on the conservative side, since we reduced the undermuff LAeq8 by the maximum 12.8 dBA to calculate the equivalent freefield level. Furthermore, the data sample size for the earplug tests with high injury percentage was quite small. Nevertheless, the results seem to support the use of LAeq8=85 dB for unprotected ears for airbag noise assessment. Frontal airbags generally produce LAeq8 from 75 to 90 dB, but the trend of depowering continues. Side airbags may pose a different kind of concern since it deploys right next to the ear. The prediction of permanent injury risk rate with exposure level would require further analysis of the chinchilla injury data.

Jaycor was invited to be a member of the Impulse Noise Task Force of the SAE Inflatable Restraints Standards Committee of the Society of Automotive Engineers. We reviewed a proposed draft document from SAE on "Impulse Noise from Automotive Inflatable Devices." This document contains a broad collection of background information on noise. However, a key component of this document was based on the Army Research Laboratory (ARL) ear model prediction results with no validation. The ARL model claims that, due to frequency effects, the same airbag poses higher hearing risk with the windows open than closed, even though test data show the noise level is lowered significantly when the windows are open. In other words, the ARL model claims the louder the bag the safer for the ear. On the other hand, the ARL airbag cat test data does not even support this trend. Furthermore, some limited field data from Renault in Europe show the opposite trend, namely, a person's hearing was damaged when the window was closed while another was not injured when the window was open for the same vehicle involved in minor accidents with airbag deployments. Dr. R. Price used the Renault data in the ARL model that predicted trends opposite to the observed data. We were also asked by Dr. G. Smoorenburg to review his latest report on impulse noise DRC, which also raised concerns similar to ours regarding the ARL model. We provided our advice to NHTSA and voiced our concerns to the SAE Task Force.

9. Products

Product 1. INJURY 7.1 Computer Code for Nonauditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.

Product 2. BOP-HHA 1.0 Computer Code for Nonauditory Health Hazard Assessment, Jaycor, Release date October 6, 2003.

Product 3. Masiello, P. J., and J. H. Stuhmiller (2003). "A Thoracic Injury Criterion for Exposure to Air Blast," Final Report J299753-03-105, October 2003.

Product 4. Masiello, Paul J. (2003). "Blast Test Device Comparisons," Jaycor Technical Report J2997.24-03-196, June 2003.

Product 5. Masiello, Paul J. (2002). "Side Impact Rib Fracture Injury Analysis," Injury Biomechanics Research, Proceedings of the Thirtieth International Workshop, Point Vedra Beach, Florida, November 10, 2002.

Product 6. Vander Vorst, M.J, Stuhmiller, J., Ho, K., Yoganandan, N. and Pintar, F. (2003), "Statistically and Biomechanically Based Criterion for Impact-Induced Skull Fracture," Proceedings of the 47th AAAM Annual Conference, Lisbon, Portugal.

Product 7. Vander Vorst, M.J and Long, D.W. "JARI IISYS Session" (June 2003)

Product 8. Vander Vorst, M.J., Bulls Eye Tekscan sensor, (April 2003)

Product 9. Vander Vorst, M.J., Dynamic calibration test device for Bulls Eye sensor (May 2003).

Product 10. Chan, P., Ho, K., and Lu, Z, "Evaluation of Hybrid III and THOR Dummy Head/neck Responses to Airbag Load at Close Proximity," paper presented at 2003 International IRCOBI Conference on the Biomechanics of Impact with AAAM, September 24-26, 2003, Lisbon, Portugal.

Product 11. 24-Channel signal conditioner for FlexiForce sensors

Product 12. Chan, P. and Lu, Z., "Development of Methodology to Measure Airbag Contact Load," paper to be presented at the 31st International Workshop on Injury Biomechanics Research sponsored by NHTSA, October 26, 2003, San Diego, CA.

Product 13. Lu, Z. and Chan, P., "Out-of-Position Airbag Load Sensitivity Study," Paper submitted to SAE 2004 World Congress, March 8-11, 2004, Detroit, Michigan.

Product 14. Chan, P. and Lu, Z., "Laboratory Study of Hybrid III and THOR Dummy Head/Neck Responses to Airbag Load at Close Proximity," paper submitted to SAE 2004 World Congress, March 8-11, 2004, Detroit, Michigan.

Product 15. SIMon Simulated Injury Monitor Version 1.0 Beta Computer Code, Jaycor, Dr. Paul J. Masiello, November 15, 2001. Released and distributed at 2001 Annual Stapp Conference, San Antonio, Texas.

Product 16. Bandak, F.A., Zhang A.X., Tannous, R.E., DiMasi, F., Masiello, P. and. Eppinger, R., "SIMon: A Simulated Injury Monitor; Application to Head Injury Assessment," 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Amsterdam, Netherlands, June 4-7, 2001.

Product 17. Kan, K.K. and Masiello, P.J., "Implementation of Euler Angles in the NAP Computational Model," Jaycor Technical Report J2997.104-02-169, February 2002.

Product 18. SIMon Simulated Injury Monitor Version 3.0 Computer Code, Jaycor, Dr. Paul J. Masiello, October 26, 2003. To be released and distributed at 2003 Annual Stapp Conference, San Diego, California.

Product 19. Kan, K.-K., K. Ho and Chan, P. C. (2003). "Use of INJURY on Thermobaric Blast Waves," Jaycor Report J3193-03-199.

Product 20. Lightweight Blast Test Device.